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Research on reasonable winding angle of ribbons of Flat Steel Ribbon Wound Pressure Vessel

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Abstract: Flat Steel Ribbon Wound Pressure Vessels (FSRWPVs) are used in many important industry areas. There is no such kind of pressure vessel exploding on operation for its reasonable structure design. Many explosion experiments on Flat Steel Ribbon Wound Pressure Vessel showed that their limited load pressure is related to the winding angle of the steel ribbons. FSRWPVs with reasonable winding angle have better security and lower cost. Reasonable angels given at the end of this paper facilitate engineering design.

Key words: Flat Steel Ribbon Wound Pressure Vessel (FSRWPV), Winding angle, Ribbons

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INTRODUCTION

Axial strength is viewed as the most important parameter in the failure analysis of a pressure vessel. As axial damage is destructive, special attention should be paid to it. The axial strength of an FSRWPV has close relationship with the winding angle α as shown in Fig.1 (Zhu *et al*., 1995). ASME CODE (1996-1997) stipulates that winding angle of 15°~30° should be used, with nothing said about how the range was determined. In fact, 15°~30° winding angle is not suitable for every FSWPV (Zhu and Wu, 1993). Since winding angles are involved in the design and manufacture of these vessels (Zhu and Huang, 1994), in this paper, explanations and conclusions about the winding angle are given based on experimental researches and engineering practice.

THEORETICAL ANALYSIS

For a pressure vessel with thin wall proportion, the average axial stress σ_a is half of the hoop stress σ_h (Huang, 1992). For an FSRWPV, the inner shell axial stress can be controlled by adjusting the winding angle α (Huang, 1993) and prestressing in the steel ribbons (Zheng, 1992). The winding of steel ribbons and the friction force between them (Yu, 1999), improves the axial strength of the FSRWPV (Zheng, 1995).

Ignoring friction

If the friction is ignored, the thickness ratio ϕ of the inner shell to wound layer is constant, and if all the steel ribbons have the same prestress, then the axial strength only varies with α. The strength of an FSRWPV can be controlled by adjusting α. When the axial stress is equal to the hoop stress under optimum condition, α can be calculated as follows:

$$\sigma_a=\sigma_h, \tag{1}$$

where, σ_a is axial stress of FSRWPV, σ_h is hoop stress of FSRWPV.

Usually there is prestressing in steel ribbon of FSRWPs, so that when the pressure vessel is operating, the hoop stress in the wall is almost uniform across the wall thickness. Application of Eq.(1) yields to Eq.(2):

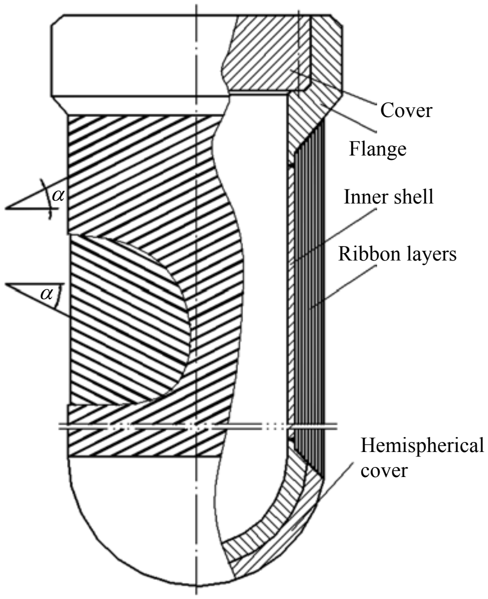

Fig.1 Structure of FSWPV

$$\delta_a=\delta_h/2, \tag{2}$$

δ_a is axial bearing thickness. Fig.2 shows that stresses of steel ribbons have the following relationship $\sigma_T\delta_w h\sin\alpha=\sigma_a\delta_w h/\sin\alpha$, so that $\sigma_a=\sigma_T\sin^2\alpha$. This means that the effective bearing thickness of steel ribbons is $\delta_w\sin^2\alpha$, so $\delta_a=\delta_i+\delta_w\sin^2\alpha$. For the same reason,

$$\delta_h=\delta_i+\delta_w\cos^2\alpha,$$

where, δ_h is thickness of hoop bearing, δ_i is thickness of inner shell, δ_w is thickness of flat steel ribbon wound layer, σ_T is axial direction stress of steel ribbons.

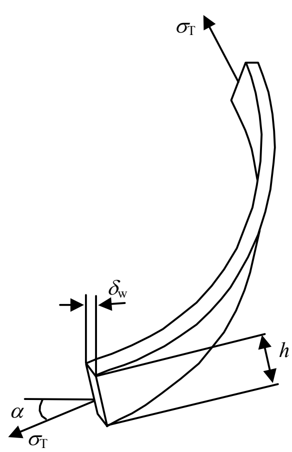

Fig.2 Ribbon force figure

That is:

$$\delta_i+\delta_w\sin^2\alpha=(\delta_i+\delta_w\cos^2\alpha)/2.$$

As $\phi=\delta_i/(\delta_i+\delta_w)$, where ϕ is the ratio of thickness ranging from 1/6 to 1/4 (ASME CODE, 1996-1997), subttituting ϕ into the above equations yields $\sin^2\alpha$ after dividing by ϕ:

$$\sin^2\alpha=(1-2\phi)/[3(1-\phi)], \tag{3}$$

and

$$\alpha=\arcsin\sqrt{\frac{1-2\phi}{3(1-\phi)}}. \tag{4}$$

For conventional pressure vessel steel, when ϕ=1/4, from Eq.(4), α=28.13°, and when ϕ=1/6, α=31.1°.

A different angle corresponds to each selected ϕ. FSRWPVs manufactured with this winding angle will have the same strength in the axial and hoop directions.

Considering friction

In fact, the action of friction force is very important. Experiments showed that the measured axial stress is only about 50% of the theoretical value when friction is ignored. Friction force affects axial strength and so must be considered. According to ASME Code Case 2229, the axial strengthening action of the frictional force of an FSRWPV is considered in the effective thickness of bearing pressure. That is:

$$\delta_a=\delta_i+\delta_w(\sin^2\alpha+f\cos^2\alpha), \tag{5}$$

where, δ_a is axial effective thickness (mm), α is winding angle of steel ribbons, f is friction coeficient, for mild steel, f=0.4; for stainless steel, f=0.3 (Zhu and Zheng, 1995).

For the same reason, hoop effective thickness is:

$$\delta_h=\delta_i+\delta_w(f\sin^2\alpha+\cos^2\alpha). \tag{6}$$

Assume that the axial stress is equal to the hoop stress, with δ_a and δ_h as given by Eqs.(5) and (6), leads to the following equation:

$$\delta_i+\delta_w(\sin^2\alpha+f\cos^2\alpha)=(\delta_i+\delta_w(f\sin^2\alpha+\cos^2\alpha))/2.$$

Subttituting ϕ into the above equations, there is:

$$\sin^2\alpha = \frac{1-2\phi-2f(1-\phi)}{3(1-\phi)(1-f)}. \quad (7)$$

So

$$\alpha = \arcsin\sqrt{\frac{1-2\phi-2f(1-\phi)}{3(1-\phi)(1-f)}}.$$

When f=0.3, ϕ=1/4, α=10.26°; when f=0.3, ϕ=1/6, α=18.0°.

Considering that friction coefficient f may be very small (the worst condition is f=0.0), and axial strength is usually less than hoop strength, an upper limiting winding angle of 30° is appropriate. In addition, if the winding angle α>30°, the hoop strength will decrease. When friction coefficient is f=0.3, ϕ=1/4, the lowest limiting winding angle is 10.26°. After calculation, we found that if friction is considered, and ϕ=1/4, α should be a smaller angle. But when ϕ=1/6, α should be a larger angle. While there are still some unknown factors, for the sake of safe operation, low winding angle of 15° should be used. Experiment also showed that the above range of winding angles is appropriate.

EXPERIMENTAL ANALYSIS

Theoretical analysis and experiments proved that FSWPVs have enough strength if the winding angle α is 15° to 30°.

Axial strength measurement

An experimental FSRWPV was built to test its strength in the axial direction. The vessel parameters (ϕ=1/6) are: Inner diameter of inner shell: 500 mm; Outer diameter of inner shell: 520 mm; Steel ribbon norms (width/thickness): 80 mm×4 mm; Length of FSRWPV: 1600 mm; Design pressure: 32.0 MPa; Winding angle α: 27°; Winding prestress: 100 MPa. The material of inner shell and steel ribbon is 16MnR (BS1501-223). There are a total of 12 layers of steel ribbons wound with the same prestress. After the manufacture of FSRWPV was finished, the shrinking of the axial length was recorded in Table 1.

Table 1 The shrinking of the axial length

Position in FSRWPV	Shrinkage of axial length (mm)
0°	0.40
120°	0.73
240°	0.65
Average	0.58

The locations of the measuring points are shown in Fig.3. Each point is measured 3 times and the mean shrinking value is recorded as the final result.

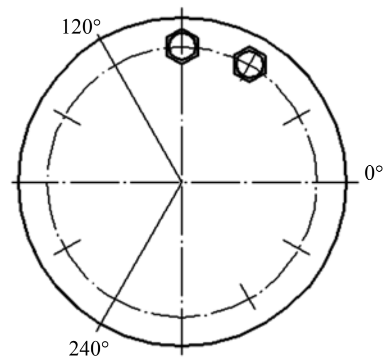

Fig.3 Position of measurement point

First, the vessel was loaded with inner pressure of 34.0 MPa, and held for 1 h. After the pressure was released, there was a permanent deformation of 0.14 mm along the vessel's axial direction. Then the vessel was loaded with pressure of 30.0 MPa, and held for 1 h and then released. No more permanent deformation was found. This proves that the stress condition of the vessel is stable. After the experiment, we found that the inner shell resumes its original shape under the inner pressure of 22.0 MPa, which means that the axial stress in the inner shell is zero. When the inner pressure increases to 32.0 MPa (the operating pressure), the axial stress of the inner shell is only 18.38 MPa, showing that the structure is stable (Zheng, 1992).

We designed another experiment, in which the vessel was wound with changing prestress of steel ribbons. The vessel parameters are: Material: 16Mn; Inner diameter of inner shell: 500 mm; Outer diameter of inner shell: 536 mm; Steel ribbon norms (width/ thickness): 80 mm×6 mm; Length of FSRWPV: 1650 mm; Design pressure: 32.0 MPa; Winding angle α: 26°; Thickness of wound layer: 60 mm. The prestress are listed in Table 2. After the manufacture of the FSRWPV was finished, the shrinkage of the axial length was 1.69 mm. When the vessel was under inner pressure of 22.0 MPa, the axial shrinking deformation was 0.33 mm. When the inner pressure increased to 40.0 MPa, the axial shrinking deformation was 0.06 mm. So the inner shell of this vessel has negative stress when operating (Zheng, 1997).

Table 2 Prestress in each layer

Layer No.	Prestress (MPa)
1	220
2	200
3	180
4	180
5	180
6	180
7	140
8	140
9	140
10	100

The above two experiments revealed that FSRWPVs have good axial strength and hoop strength if their steel ribbons are wound at less than 30° angle.

Strength measurement in different winding angle

Three FSRWPVs were built to test the influence of the winding angle upon the axial strength. All three FSRWPVs had the same shape and parameters except the winding angle α. FSRWPVs parameters are: Inner diameter of inner shell: 147.3 mm; Outer diameter of inner shell: 152.3 mm; Steel ribbon norms (width/thickness): 15.9 mm×1.0 mm; Length of FSRWPV: 1200 mm; Layers: 14; Winding angle α: 26°; Thickness of ribbon layer: 14 mm. The material of the steel ribbon was 16MnR (BS1501-223) whose yield stress is 378.0 MPa and ultimate tensile strength is 513.6 MPa. The inner shell material was Q215-B (BS1499-34/20) whose yield stress is 222.5 MPa and ultimate tensile strength is 330 MPa. There was no prestressing in the steel ribbons. The winding angles were 20°, 15° and 10° respectively. Explosion experiment results are shown in Table 3.

From the above experiments, we can conclude that when the winding angle is less than 15°, the inner shell is in dangerous condition of circle rupture. So the lower allowable limited winding angle α should be 15° (Zheng, 1999).

CONCLUSION

Theoretical and experimental analyses showed that when the winding angle α of a FSRWPV is less than 15°, there is danger of axial breaking, and when the winding angle α is bigger than 30°, the entire vessel capability of bearing the internal pressure would decrease. Considering that either there is enough axial strength or the hoop strength is not reduced too much, and considering the impact of the frictional force, the winding angle of steel ribbon should be in the range of 15°~30°.

In FSRWPV designing, the ratio ϕ of inner shell thickness to steel ribbons layer thickness is an important factor. When ϕ is near 1/4, a smaller winding

Table 3 Explosion experiment results

Vessel No.	Wound angle	Explosive pressure (MPa)	Explosion character
1	20°	60.3	Two ends of FSRWPV had a small about 2° rotation angle. The vessel body had a small curve at the place 520 mm away from one end. At rotated and cured place, displacement between steel ribbons increased from 2 mm to 6 mm. There was a 10 mm crack at curved place. No steel ribbons broke off
2	15°	58.8	Two ends of FSRWPV had an obvious about 10° rotation angle. The vessel body had a curve at the place 380 mm away from one end. At rotated and cured place, displacement between steel ribbons increased obviously from 2 mm to 11 mm. There was a half circle crack. No steel ribbons broke off
3	10°	51.0	Two ends of FSRWPV had an obvious about 12° rotation angle. The vessel body had an obvious curve at the place 167 mm away from the end. At rotated and cured place, displacement between steel ribbons increased obviously from 2 mm to 12 mm. The whole inner shell broke off at the cured place. There were 6 steel ribbons (outermost layer 4 and outer second layer 2) breaking off

angle should be used. When ϕ is near 1/6, a bigger winding angle should be used.

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