A Review of Research on Multilayered Vessels

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Abstract. Multilayered vessels have been widely applied in engineering fields due to their unique layered characteristics, attracting considerable attention from researchers. Significant progress has been made in exploring key aspects. However, challenges remain regarding the universality of theoretical models, the precision of numerical simulations, and the comprehensiveness of experimental validations. This review systematically summarizes recent advances in this domain, providing a detailed chronological analysis of key research areas. Furthermore, the study identifies existing limitations and proposes potential directions for future research, aiming to offer a theoretical basis for optimizing the design and improving the performance of multi-layered containers.

Keywords: multilayered vessel; prestressing; thermal stress; interlayer gap

1 Introduction

In 1930, A. O. Smith Corporation in the United States first proposed a multilayered wrapped cylinder structure processed by tensioning steel plates with steel wire, as shown in figure 1. This innovation not only met the industrial demands for high-pressure vessels at that time but also laid the foundation for the subsequent design and development of multilayered vessels.

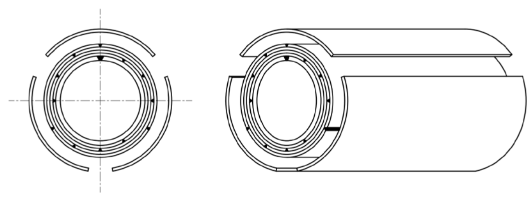

Fig. 1. Multilayered cylinder structure of the A. O. Smith.

In the late 1970s, Germany's Krupp Corporation introduced improvements to the multilayered structure developed by A. O. Smith Corporation, creating an integrated multilayered vessel, as shown in figure 2. In this design, all longitudinal and circumferential weld seams were distributed separately, with the circumferential weld seams of adjacent layers offset axially by a certain distance and the longitudinal weld seams of adjacent layers staggered at specific angles in the circumferential direction. The integrated multilayered vessel developed by Krupp Corporation demonstrated a range of comprehensive advantages, establishing itself as an ideal structure for multi-layer composite high-pressure vessels.

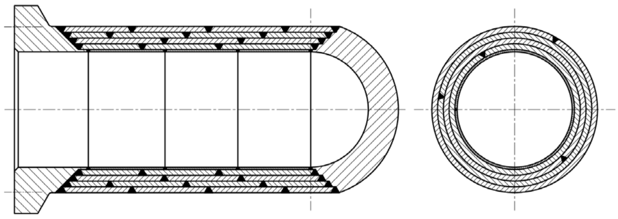

Fig. 2. Multilayered cylinder structure of the Krupp.

Since the advent of multilayered vessels, they have been widely applied in industries such as hydrogenation reactors, ammonia synthesis towers, and supercritical CO_2 extraction. Notably, China's first high-pressure vessel also adopted this structure. With the advancement of energy utilization, multi-layer wrapped vessels, recognized as a safe and reliable design, are now being extensively promoted for large-capacity high-pressure gaseous hydrogen storage, as shown in figure 3.

(a) Ammonia Tower (b) High Pressure Extractor (c) H_2 Storage Tank

Fig. 3. Practical application of multilayered vessels.

Due to the layered characteristics of multilayered vessels, numerous scholars have conducted studies on aspects such as the contact states between layers, stress states involving gaps, prestressing conditions, self-reinforcement or overpressure treatment, and thermal stress. owever, studies on the fatigue issues of multilayered vessels are currently scarce. To identify the shortcomings of existing studies and establish the next steps for research, it is necessary to summarize and analyze previous work. This paper will present important past research in various areas in chronological order and highlight the limitations of current research, while also proposing directions for further investigation.

2 Research on Contact States between Layers

In 1989, Wu et al.[1] divided the adjacent layers of multilayered vessels along the circumferential symmetrical plane of the cylindrical longitudinal weld seams, resulting in the friction zone and Lame zone. Based on the mechanical continuity conditions and stress continuity at the interface, they derived the calculation formula for the inter-layer friction angle of each layer, as shown in Eq.(1):

$$\alpha_j = \frac{1}{2f}\ln\left(\frac{R_{j+1}}{R_j}\cdot\frac{R_{n+1}^2 - R_j^2}{R_{n+1}^2 - R_{j+1}^2}\right) \tag{1}$$

From the Eq.(1), it can be deduced that to avoid the overlapping of the friction zones between adjacent layers, the angle by which the longitudinal weld seams of adjacent layers should be offset in the circumferential direction must be greater than twice the value of α_{n-1}. Therefore, the condition is:

$$\beta \geqslant \beta_{\min} = 2\alpha_{n-1} = \frac{1}{f}\ln\left(\frac{R_n}{R_{n-2}}\cdot\frac{R_{n+1}^2 - R_{n-1}^2}{R_{n+1}^2 - R_n^2}\right) \tag{2}$$

Subsequently, in 1993, Wu et al.[2], building upon the research on circumferential friction forces, considered the influence of axial friction forces between the layers. The study proposed that, to ensure the axial friction force between the layers can effectively carry the axial load, there must be a continuous contact region of a certain length between adjacent layers. The minimum contact length is given by Eq.(3):

$$l_{\min} = \lambda\pi R_0^2\left(k^2 - 1\right)\left\{2f\left[\sum_{j=0}^{n-1}\left(k_{j+1}^2 - 1\right)\left(\pi - \alpha_j - \alpha_{j+1}\right)R_{j+1} + \sum_{j=1}^{n-1}\frac{R_{j+1} - R_j}{f}\left(1 + k_j \cdot k_{j+1}\right)\right]\right\} \tag{3}$$

In 2023, Alaydin et al.[3] investigated the interaction of multilayered cylinders under friction and proposed a novel isogeometric Kirchhoff–Love (KL) shell computational method for multilayered structures. Their study revealed that interlayer friction increases the bending stiffness of the structure and induces significant hysteresis behavior.

3 Research on Stress States Involving Gaps

In 1968, Pimshtein[4], based on the uniform gap model as shown in figure 4, presented a formula for the calculation of the three principal stresses under the condition of gaps between the layers. However, the detailed derivation process was not provided in the literature. In the following year, Pimshtein[5], based on elastic-plastic theory, analyzed the stress state of multilayered cylinders with gaps. However, his conclusions were only applicable to the ideal situation where the gaps were completely eliminated under internal pressure.

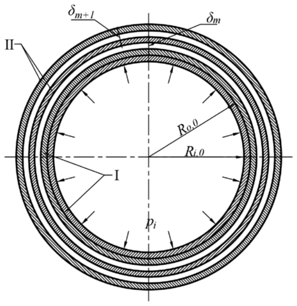

Fig. 4. Interlayer gap model.

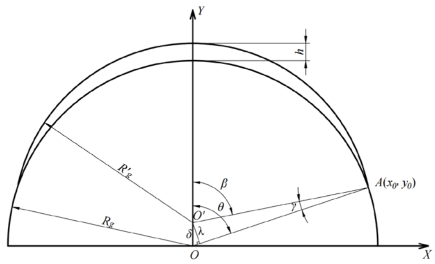

Fig. 5. Typical geometry of a gap.

In 1985, J. Rasty and M. Sabbaghian[6], building on the stress formulas derived by previous researchers based on the uniform gap assumption for layers, proposed a new gap model. The gap was approximated by two circular arcs with different radius: the inner arc radius R_g, the angular span of the gap arc corresponding to an angle of 2θ, and the maximum radial gap h as shown in figure 5. They also derived the additional strain required to eliminate such gaps, as given by Eq.(4):

$$\varepsilon_\theta = \frac{h\theta}{\pi R_g}\left[1-\frac{2+\dfrac{h}{R_g}}{2\left(1+\dfrac{h}{R_g}-\cos\theta\right)}\right]+\frac{1}{\pi}\left[1+\frac{h}{R_g}-\frac{\left(\dfrac{h}{R_g}\right)\left(2+\dfrac{h}{R_g}\right)}{2\left(1+\dfrac{h}{R_g}-\cos\theta\right)}\right]\times\arcsin\left[\frac{\dfrac{h}{R_g}\left(2+\dfrac{h}{R_g}\right)\sin\theta}{2\left(1+\dfrac{h}{R_g}-\cos\theta\right)\left(1+\dfrac{h}{R_g}\right)-\dfrac{h}{R_g}\left(2+\dfrac{h}{R_g}\right)}\right] \tag{4}$$

4 Research on prestressing

In 2011, Zhen and Jiang[7] conducted research on the prestressing of the laminates and the clamping force of the hydraulic clamping device. They proposed a more concise formula for calculating the prestressing, as shown in the Eq.(5). They also carried out an overall clamping experiment on an inner cylinder with an inner diameter of 800 mm and a thickness of 30 mm, which was wrapped with a 10 mm thick outer steel plate.

$$\sigma_{\theta mc} = \sum_{m=1}^{n}\left(-p_{mc}\cdot\frac{2K_m^2}{K_m^2-1}\right) \tag{5}$$

The experimental results showed that the hydraulic clamping device effectively generates initial prestressing at the interfaces between the layers and the inner cylinder. Moreover, the magnitude of the clamping force should not be high enough to cause plastic yielding of the laminates during the processing.

In 2022, Wang et al.[8] derives the stress calculation formulas for the inner cylinder, considering the prestress of the shell, based on the Lamé equation and different strength theories. Furthermore, an optimization design model is proposed, aiming to minimize the material cost of the shell while accounting for the prestress and the use of different materials for the inner cylinder. The model takes the thickness of the inner cylinder, the number of lamination layers, and the thickness of each layer as variables.

In 2023, Wang et al.[9]derives the stress calculation expressions for the multilayered high-pressure vessel under internal pressure, both with and without prestress, as well as the formulas for calculating the ultimate load. Numerical simulations were conducted for validation. The results show that the theoretical and numerical simulation results are in good agreement. The application of prestress significantly reduces the working stress level of the inner cylinder and effectively improves the stress state of the shell under elastic conditions, thereby enhancing the elastic load-bearing capacity of the shell.

In 2024, Xiao et al.[10], based on the ideal model without interlayer gaps and building on the work of Zhen[7], proposed a new method for calculating prestressing, as Eq.(6):

$$\sigma_m^{'} = \sigma_m - \sum_{u=m+1}^{n} \left(\sigma_u \cdot \frac{K_{m-1}^2 + 1}{K_{u-1}^2 - 1} \cdot \frac{k_u^2 - 1}{k_u^2 + 1} \cdot \prod_{v=m}^{u-1} k_v^2 \right) \tag{6}$$

They employed a finite element analysis approach with multiple loading steps to validate the accuracy of their calculation method, as shown in figure 6. Additionally, they provided the limiting conditions for prestressing under small deflection instability conditions.

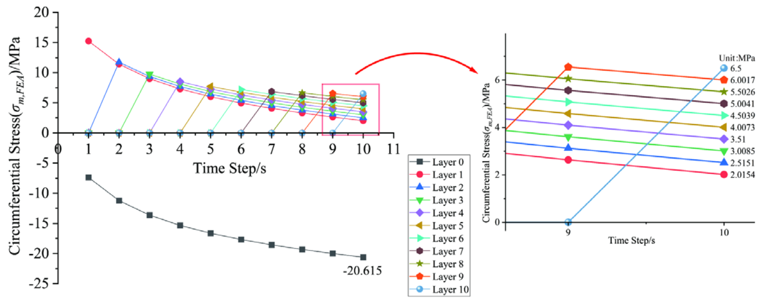

Fig. 6. FEA verification.

5 Research on Self-Reinforcement or Overpressure Treatment

In 2018, Rahman Seifi[11] investigated the maximum working pressure of shrink-fitted multi-layer containers after self-reinforcement treatment using a three-layer model that considered the Bauschinger effect and reverse yielding conditions. The results demonstrated that, compared to conventional single-layer type, the load-bearing capacity of multilayered vessels could be increased by up to two times through appropriately arranged interference fits. The findings aligned closely with the conclusions of E.-Y. Lee and N. Kumar.

In 2024, Khodayari[12] investigated the burst pressure of double-layered cylinders with internal surface cracks. The author conducted experimental and finite element analysis to study the effects of various parameters, such as crack geometry, percentage of autofrettage, and radial interference values, on the distribution of the J-integral at the crack tip and the burst pressure. This study provides a systematic investigation into the influence of cracks on the burst pressure of multilayered cylinders, offering theoretical insights and engineering guidance to enhance the design safety and service life of thick-walled cylinders.

6 Research on Thermal Stress

In 1990, Zukhova V. and Pimshtein P.[13] examined multi-layered cylinders subjected to internal pressure and internal heating. The study highlighted that the heat transfer characteristics of multilayered cylinders include the thermal resistance of the layers, the contact thermal resistance between layers, and the surface heat transfer resistance. Based on this, the steady-state heat flux can be calculated using Eq.(7):

$$q_l = \frac{2\pi\left(T_{\mathrm{me}}^{\mathrm{in}} - T_{\mathrm{me}}^{\mathrm{ou}}\right)}{\dfrac{1}{K_{\mathrm{in}} r_{\mathrm{in}}} + \sum_{i=1}^{n} \dfrac{1}{\lambda_i} \ln \dfrac{r_i}{r_{i-1}} + \sum_{i=1}^{n-1} R_i + \dfrac{1}{K_{\mathrm{ou}} r_{\mathrm{ou}}}} \tag{7}$$

In 2021, Sim et al.[14] studied the stress distribution in multi-layer hollow spherical pressure vessels under thermomechanical loads and proposed an analytical solution based on a recursive algorithm. The results show that the proposed recursive analytical method can effectively estimate the thermomechanical stress distribution in multi-layer hollow spherical pressure vessels, with the calculated results being in high agreement with those obtained from FEA, and the error being within 1%, as shown in figure 7. In the same year, Zhou et al.[15] focuses on the analytical modeling of steady-state thermal conduction in a multilayer cylinder with circumferentially-varying convective heat transfer boundary conditions.

In 2023, Jerzy et al.[16] investigated the steady-state temperature distribution in multilayer elliptical cylinders and proposed a combined analytical-numerical method to solve this problem. The results indicate that the temperature distribution within the insulating layer is approximately linear. In test systems with significantly different thermal conductivities, the temperature distribution exhibits a piecewise continuous zigzag pattern. Furthermore, the interfaces between the layers of the multilayer elliptical structure are not isothermal.

In 2024, Tokovyy et al.[17] proposed a method for solving the plane axisymmetric problem of multilayer hollow cylinders under elastic and thermoelastic conditions, applicable to cases where the material properties of each layer have an arbitrary distribution in the radial direction. The core idea of the method is to represent the distribution of material properties throughout the structure as a gradually varying function, and solve the corresponding compatibility equations using a direct integration approach, thereby obtaining the strain relationships. This method avoids the complexity of using generalized derivatives.

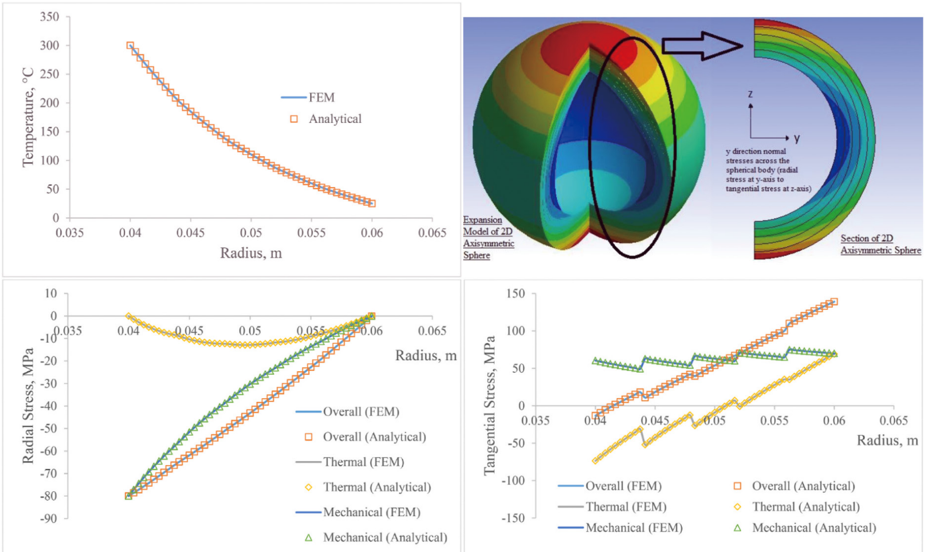

Fig. 7. Comparison of theoretical and finite element calculations[14].

7 Conclusions

Currently, the calculation of prestressing primarily considers the effects of weld shrinkage and initial wrapping force, typically assuming an ideal multilayered cylinder without gaps. However, due to the surface roughness and the ellipticity from rolling, gaps between the layers significantly affect the distribution and magnitude of prestressing. Nevertheless, during manufacturing, the prestressing of the layers accumulates, leading to large compressive stresses in the inner cylinder and an increased risk of instability. Therefore, a safe and reliable prestressing calculation method is necessary to limit the overall prestress.

Additionally, existing stress calculation formulas for multi-layer cylinders with gaps assume small gaps and overlook the impact of gap elimination on the cylinder's diameter ratio. However, as multilayered vessels increase in pressure and size, the accumulation of gaps may lead to significant errors. Thus, more accurate calculation methods are required to meet safety standards.

At present, there is a lack of research on the fatigue performance of multilayered vessels, posing certain risks in evaluating their operational reliability under fatigue conditions. Future studies should focus on the fatigue performance of these vessels through both theoretical and experimental investigations, considering factors such as loading conditions, material properties, and the characteristics of internal media.

Reference

1. Wu J, Zhu X, Chen G. Research on the leak-only, non-explosive behavior of a new type of integral multi-layer high-pressure vessel. Journal of Pressure Vessel (China), 1989(2): 25-30.
2. Wu J. Discussion on the Design Method of Integral Multi-Layer Clamped High-Pressure Vessels. Chemical Engineering Machinery, 1993, 20(1): 33-38.
3. Alaydin M D, Bazilevs Y. Multilayer Shells Interacting Through Friction[J]. Journal of Applied Mechanics, 2023, 90(121012). https://doi.org/10.1115/1.4062139.
4. Pimshtein P. Strength of multilayer high pressure vessels[J]. Chemical and petroleum engineering, 1968, 4(7): 574-578. https://link.springer.com/article/10.1007/BF01136754.
5. Pimshtein P, Tatarinov V. Elastoplastic operation of multilayer cylinders with gaps[J]. Chemical and Petroleum Engineering, 1969, 5(7): 523-528. https://link.springer.com/article/10.1007/BF01832409.
6. Rasty J, Sabbaghian M. Effect of Imperfect Contact Between Adjacent Layers on the Integrity of Wrapped Vessels. [J]. Journal of Pressure Vessel, 1985, 98: 167-176. https://doi.org/10.1115/1.3265596.
7. Liang Z, Nan J, Sijia L. Experimental Study of Integrated Multilayer Clamping High Pressure Vessel[J]. Journal of Pressure Vessel Technology, 2011, 133(6): 061206. https://doi.org/10.1115/1.4004568.
8. Wang T,Qin G,Qian C. Optimization Design of Multilayer Wrapped High Pressure Vessel Cylinder [J]. Energy Conservation Technology (China), 2022, 40 (05): 387-391+402.
9. Wang T, Qian C, Wu Z, et al. Analysis of Load-bearing Capacity of Multi-layer Wrapped High Pressure Vessels [J]. Journal of Mechanical Engineering (China),2023,59(14):169-178.
10. Xiao Z, Wang X, Wang H,. Prestressing Estimation for Multilayer Clamping High Pressure Vessel Laminates[J]. Journal of Pressure Vessel Technology, 2024, 146(5). https://doi.org/10.1115/1.4066003.
11. Seifi R. Maximizing working pressure of autofrettaged three layer compound cylinders with considering Bauschinger effect and reverse yielding[J]. Meccanica, 2018, 53(10): 2485-2501. https://link.springer.com/article/10.1007/s11012-018-0834-2.
12. Khodayari M S, Seifi R. Bursting Pressure of the Autofrettaged and Interferenced Double-Layer Cylinder with an Internal Surface Crack[J]. Journal of Failure Analysis and Prevention, 2024, 24(2): 721-735. https://doi.org/10.1007/s11668-024-01876-z.
13. Zukhova V, Pimshtein P. Thermally stressed state of a laminated cylinder exposed to internal pressure and steady-state external heating[J]. Soviet Applied Mechanics, 1990, 25(8): 808-813.
14. Sim L C, Yeo W H, Purbolaksono J, et al. Analytical solution of thermo-mechanical stresses of multi-layered hollow spherical pressure vessel[J]. International Journal of Pressure Vessels and Piping, 2021, 191: 104355. https://doi.org/10.1016/j.ijpvp.2021.104355.
15. Zhou L, Parhizi M, Jain A. Temperature distribution in a multi-layer cylinder with circumferentially-varying convective heat transfer boundary conditions[J]. International Journal of Thermal Sciences, 2021, 160: 106673. https://doi.org/10.1016/j.ijthermalsci.2020.106673.
16. Gołębiowski J, Zaręba M. The Stationary Thermal Field in a Multilayer Elliptic Cylinder[J]. Applied Sciences, 2023, 13(4): 2354. https://doi.org/10.3390/app13042354.
17. Tokovyy Y V. Elastic and thermoelastic response of multilayer inhomogeneous hollow cylinders [J]. Mechanics of Advanced Materials and Structures, 2024. https://doi.org/10.1080/15376494.2023.2186548.