

The Stability Analysis and Calculation Method for a Multilayer Composite Structure

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Abstract. Multilayer composite structures have the characteristics of high strength, high stiffness, and good corrosion resistance, and are increasingly used in underwater equipment. The stability analysis of multilayer composite structures is one of the key issues in engineering design. As an important analysis method, the analytical calculation method can achieve rapid design of structural parameters. This paper proposes an analytical method for stability calculation of multilayer composite structures based on residual pressure recursion. Through numerical experiments, the effectiveness of the method is verified, providing an option for stability analysis and engineering design of multilayer composite structures.

Keywords: Stability Analysis, Multilayer Composite Structure, Numerical Experiments, Mechanical Propertie.

1. Introduction

A multilayer composite structure consists of multiple layers made of different materials, each with distinct mechanical properties. By carefully designing the material and thickness of each layer, specific performance requirements can be met. Multilayer composite structures offer high strength and stiffness while being lightweight. Due to their excellent properties, such as high strength, high stiffness, and good corrosion resistance, these structures have been widely used in fields like aerospace, automotive, and marine industries. With advancements in material technology and manufacturing processes, multilayer composite structures, particularly in the form of pressure vessels, are increasingly applied in underwater equipment.

When subjected to external loads, pressure vessels made from multilayer composite materials may experience instability, potentially leading to structural failure. The stability of multilayer composite structures has always been a critical issue in engineering design. Accurately assessing the stability of such structures is essential to ensuring their safety and reliability.

The purpose of stability analysis is to determine the stability limit of a structure under specific loading conditions, providing a foundation for structural design. Accurate stability analysis can prevent instability failures during the structure's operation, thus enhancing the safety and reliability of the design. Allen explored the stability results of damped multilayer composite beams and plates, formulating the motion equations of such structures as partial differential equations and using semigroup theory to prove the stability of damped multilayer beams and plates. Additionally, Allen studied the semigroup stability and optimal damping problems related to these models [1]. Muc discussed experimental and theoretical studies on the buckling loads of multilayer composite plates and shells, presenting a broad literature review, with a focus on the buckling and post-buckling behavior of structures with notches and reinforcements [2]. Tian et al. investigated the stability of the interface during the cold rolling of multilayer Ag-Cu composites. They found that the heterogeneous twin boundaries deviated from ideal twin orientations, yet after cold rolling, the cubic interlayer orientation relationship was preserved, and some deformation twins formed in both phases could pass through the Ag/Cu interface in a continuous manner [3]. Zeng et al. examined the stability of mesoscopic multilayer structures induced by the Casimir effect, focusing on the formation of restoring Casimir forces and how these forces stably balanced the layers of the structure, discussing the stable equilibrium distances between layers and the effects of metamaterial characteristic frequencies and layer thickness [4]. Bin et al. proposed an accurate quasi-3D zigzag beam theory for

the free vibration and stability analysis of multilayer composite beams under thermomechanical loads [5].

The aforementioned analysis methods are primarily used to evaluate the stability of multilayer composite structures based on design outcomes. However, they lack efficient methods for quickly determining parameters, such as the thickness of each layer, during the design stage. This paper proposes an analytical calculation method for the stability of multilayer composite structures, which can be applied to the stability design of cylindrical structures under external pressure, thus providing reasonable design parameters such as the interlayer thickness.

2. Stability Calculation Method for Multilayer Composite Structures Based on Residual Pressure Recursion

Currently, methods for analyzing plate and shell structures primarily include numerical calculations and theoretical analysis. Among these, numerical methods are predominantly based on the finite element method (FEM). FEM is one of the most widely used numerical approaches for structural stability analysis. It is highly flexible in handling multilayer composite structures with complex shapes, material properties, and boundary conditions. By discretizing the structure into a finite number of elements, the element stiffness matrix and global stiffness matrix are established, allowing for the calculation of the structure's displacements and stresses, which helps in determining its stability. Finite element software, such as ABAQUS and ANSYS, plays a significant role in the stability analysis of multilayer composite structures, and there are numerous successful engineering cases where FEM has been applied for stability checks in structural design.

Theoretical analysis methods are generally based on plate and shell theories, such as Mindlin plate theory, to analyze the stability of multilayer composite plate and shell structures. These theories can account for factors like geometric shape, material properties, and boundary conditions to a certain extent. By establishing governing equations, they help to solve for critical loads and instability modes of structures. However, the calculation methods for multilayer structural stability are not yet fully developed. In this paper, we attempt to extend the classical single-layer plate and shell stability calculation method to multilayer composite structures through iterative calculations, applying it to stability design. The following sections will provide a detailed introduction to the proposed calculation method.

Without loss of generality, a cylindrical structure subjected to external pressure is taken as the object of study. According to the strength and stability requirements for a single-layer cylindrical material under compression, the allowable pressure can be calculated using the following method:

$$p_{cr} = 2.2E \left(\frac{t}{D_o} \right)^3 \quad (1)$$

In the formula, D_o represents the diameter of the cylinder, t is the thickness. The calculated result shows that if $P \leq P_0$, the structure satisfies the stability requirements.

If a stability safety factor is introduced as α , the allowable pressure can be expressed as:

$$p_{cr} = \frac{2.2E}{\alpha} \left(\frac{t}{D_o} \right)^3 \quad (2)$$

This equation is widely used in engineering applications and has been validated through extensive practical testing. The following section extends this method to multilayer structures. The detailed calculation method is as follows:

First, calculate the allowable pressure for the first layer of the structure:

$${}^1p_{cr} = 2.2E_1 \left(\frac{t_1}{D_o} \right)^3 \quad (3)$$

If the actual pressure is less than the critical pressure, the structure is considered safe, and the calculation ends.

If $p_1 \geq {}^1p_{cr}$, there is a possibility of instability, and the calculation proceeds to Step 2.

Introduce a new parameter — residual pressure. This refers to the pressure remaining after the load is transmitted through the first layer to the next layer. The residual pressure is calculated as:

$$p_2 = \frac{\pi(D_0 - 2t_1)h}{\pi D_0 h} (p_0 - {}^1p_{cr}) = \frac{D_0 - 2t_1}{D_0} (p_0 - {}^1p_{cr}) \quad (4)$$

Next, calculate the critical pressure for the second layer:

$${}^2p_{cr} = 2.2E_2 \left(\frac{t_2}{D_o - 2t_1} \right)^3 \quad (5)$$

If the residual pressure acting on the second layer is less than the critical pressure of the second layer, the structure is considered safe, and the calculation ends.

If $p_2 \geq {}^2p_{cr}$, there is a possibility of instability, and the calculation proceeds to the third layer.

This process is repeated iteratively until the thickness of the layers satisfies the stability requirements.

3. Calculation Example and Verification

Figure 1 shows a typical geometric model of an underwater structure's hull. Traditional structures typically use a single-layer design made of alloy steel. To enhance structural stiffness and reduce weight, a three-layer composite structure is proposed. The sandwich material structure is illustrated in Figure 2.

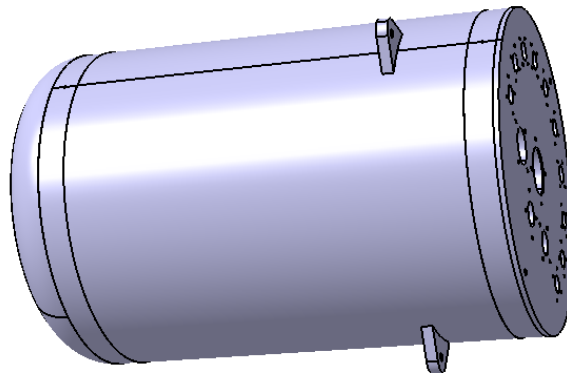


Figure 1. Geometric Model of the Hull of an Underwater Structure

If a traditional structural approach is adopted, using a single-layer high-strength steel as the hull material, the design results obtained based on Equation (2-2) are shown in the table below.

Table 1. Design Parameters for Single-Layer High-Strength Steel Hull

No.	Symbol	Parameter Name	Value	Unit
1	α	Safety Factor	4.0	
2	E	Elastic Modulus	2.06E+11	Pa
3	D_o	Diameter	300.0	mm
4	t	Design Thickness	9.413	mm

If a multi-layer structure is adopted, using the three-layer composite material cabin body shown in Figure 2, the design results can be obtained based on equations (2-3) to (2-5), as presented in Table 2.

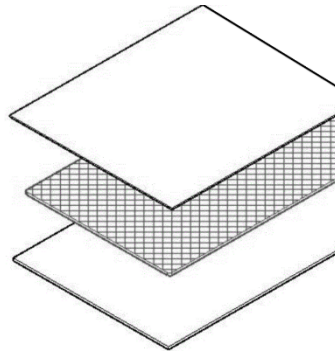


Figure 2. Schematic diagram of sandwich material structure

Table 2. Design parameter table for three-layer composite cabin body

No.	Symbol	Parameter Name	Value	Unit	
1	α	Safety Factor	4		
2	D_o	Diameter	300	mm	
3	E	Outer Layer Elastic Modulus	2.06E+11	Pa	
		Intermediate Layer Elastic Modulus	4.00E+09	Pa	
4	t	Design Thickness	Outer Layer	3	mm
			Intermediate Layer	19.6	mm
			Intermediate Layer	3	mm

To validate the effectiveness of the analysis results mentioned above, the finite element method was employed using the commercial software ABAQUS to analyze the design results. Figure 3 shows the mesh model of the hull structure.

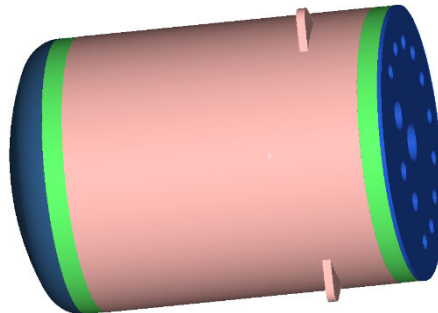


Figure 3. Mesh model of the hull structure

The first-order characteristic buckling mode of the hull under an external pressure of is illustrated in Figure 4, with a corresponding eigenvalue of 4.16. This is generally consistent with the results obtained using the method proposed in this paper.

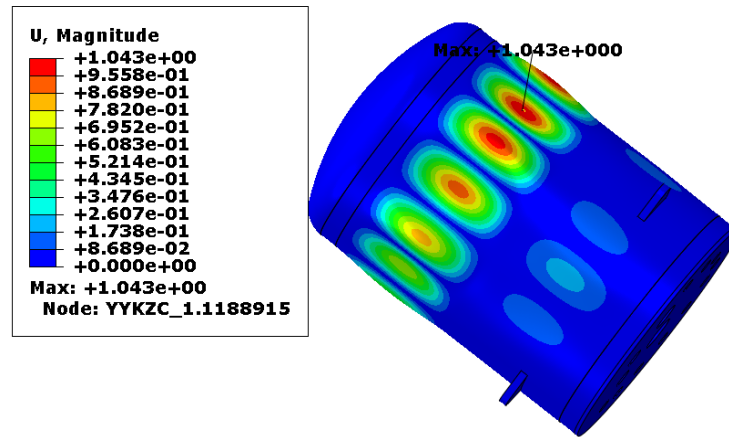


Figure 4. First-order buckling mode of the hull under external pressure

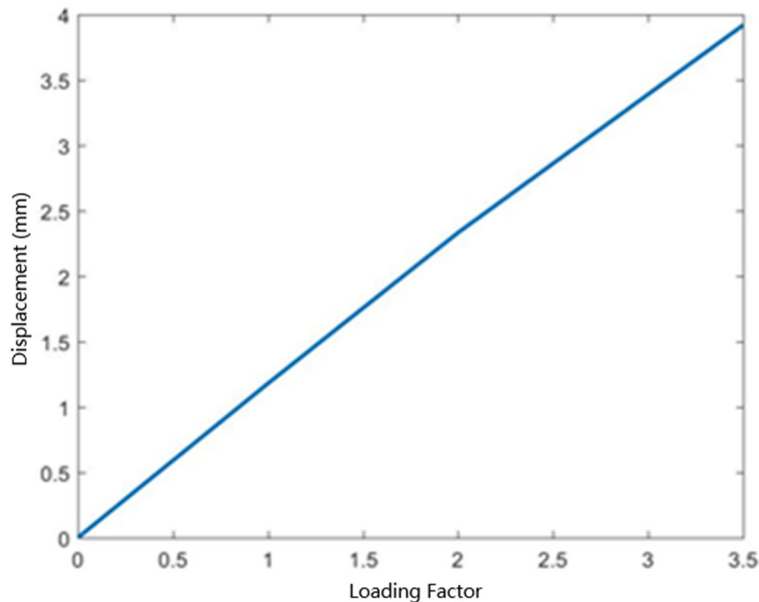


Figure 5. Load-displacement curve under external pressures

Figure 5 presents the relationship curve between the maximum displacement on the hull surface and the applied load obtained through nonlinear buckling analysis in ABAQUS. From the figure, it can be observed that within the applied load range, the displacement does not exhibit sudden increases, indicating that the structure meets the stability requirements.

4. Conclusion

The stability analysis of multilayer composite structures is one of the key issues in engineering design. Analytical methods, as an important means of analysis, can provide an in-depth understanding of the stability of multilayer composite structures and offer a theoretical basis for engineering design. This paper presents an analytical method for stability calculation of multilayer composite structures based on residual pressure iteration. Numerical tests have validated the effectiveness of this method, providing a rapid calculation option for stability analysis and engineering design of multilayer composite structures.

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