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A Study on the Bending Instability and Wrinkling Characteristics of Thin-Walled Circular Tubes Stiffened with Pads

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ABSTRACT

To investigate the bending instability and wrinkling characteristics of thin-walled circular tubes reinforced with pads, a three-dimensional finite element model of the thin-walled tube was developed, followed by an eigenvalue buckling analysis. The influence of the geometric parameters of the thin-walled tube on the buckling factor and buckling modes was analyzed. The study found that the length of the pad has a significant impact on the load-bearing capacity; results indicate that a longer pad leads to a lower load-bearing capacity of the thin-walled tube. As the thickness of the pad increases, the buckling factor of the thin-walled tube generally shows a decreasing trend. Conversely, as the angle of the pad increases, the buckling factor generally exhibits an increasing trend.

KEYWORDS

Pad stiffening; Thin-walled circular tubes; Bending instability; Wrinkling behavior; Finite element simulation

1 Introduction

Thin-walled circular tubes are commonly used structural components in various engineering fields such as construction, machinery, and aerospace [1-4]. During cold bending forming processes, instability-induced wrinkling can occur in tubes due to the interaction of multiple factors [5-6], which compromises their service performance and aesthetic appearance.

Wrinkling is a major defect in tube bending. One method to control wrinkle formation is to reinforce the tube with pads. Considerable research has been conducted on the instability and wrinkling of thin-walled circular tubes. For instance, Yang Shijun [7] investigated the bending performance of thin-walled circular steel tubes with large diameter-to-thickness ratios, analyzing the effects of parameters such as steel yield strength, normalized diameter-to-thickness ratio, and initial geometric imperfections on the member's bending behavior. Lin Bingbing [8] studied the influence of forming parameters on the bending quality of thin-walled tubes based on numerical control (NC) rotary draw bending. Li Yang [9] proposed a critical wrinkling criterion considering through-thickness stress and conducted extensive research. Chai Wei et al. [10] derived an empirical formula for the critical local radial load under external pressure based on stability analysis of externally pressurized thin-walled cylindrical shells under local radial loading. Gao Sheng et al. [11] investigated the prediction of free bending instability wrinkling and deformation patterns in tubes using the energy method. Chen Dongfen [12] studied the static performance of square steel tube joints strengthened with pads and collar plates. Yayun YU et al. [13] proposed a reinforcement design inspired by bamboo nodes, exploring elastic buckling analysis and optimization of thin-walled bamboo tube beams under bending loads. Zhaoyu Xu et al. [14] examined the nonlinear stability of thin elastic elliptical cylindrical shells under uniform bending, establishing reference equations for the Brazier ovalization collapse mode of long elliptical thin-walled cylinders. Abdullah Mahmoud et al. [15] developed and validated a practical finite element modeling protocol for simulating the bending failure of thin-walled spiral-welded conical tubes. Wenbin Wu et al. [16] conducted a theoretical analysis of the wrinkling behavior of inflated tubes under pure bending, studying the morphological evolution in the post-buckling stage through numerical results. The research team led by Academician Zhou Xuhong [17], focusing on conical steel towers for wind turbines simplified as thin-walled circular steel tubes, designed I-shaped and T-shaped stiffeners for reinforcement and conducted experimental studies on their mechanical performance under combined compression and bending. However, no existing literature specifically addresses the buckling and wrinkling characteristics of pad-stiffened thin-walled circular tubes under bending. Therefore, this paper aims to conduct a more in-depth investigation into the bending instability and wrinkling behavior of thin-walled circular tubes reinforced with pads.

This study investigates the bending instability and wrinkling characteristics of thin-walled circular tube members reinforced with pads, primarily utilizing the finite element method to simulate the behavior of pad-stiffened thin-walled circular tubes under bending.

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2 Thin-Walled Circular Tube Model

2.1 Geometric Model

For the circular tube member, the inner diameter is D= 1400 mm, the length is L= 6000 mm, and the wall thickness is T = 14 mm. For the stiffener pad, the initial length is a= 400 mm, the initial thickness is t= 14 mm, and the pad angle is θ= 63.75°.

2.2 Finite Element Model

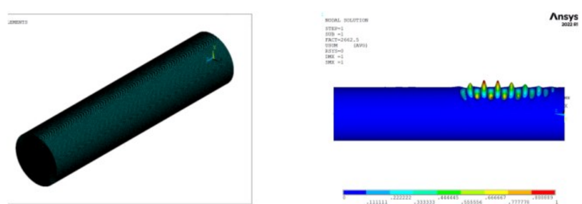
The material properties of the thin-walled circular tube are as follows: Poisson's ratio ν = 0.3, and Young's modulus E = 200,000 N/mm^2. A finite element model was developed according to the actual dimensions of the thin-walled circular tube. The element types selected include the shell element Shell181 and the RBE3 element.

2.3 Loads and Boundary Conditions

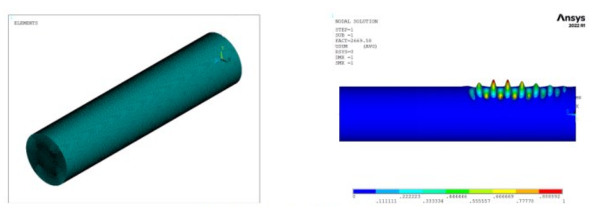
For the definition of boundary conditions, all nodes on the starting end face of the thin-walled circular tube (i.e., the working plane where the coordinate system is located) are selected and constrained in the X, Y, and Z translational degrees of freedom. A central node is created at the center of the tube's terminal end face. Using this central node and all nodes located along the radius of the terminal end face, an RBE3 element is constructed. This ensures that the end face remains rigid and does not deform when a bending moment is applied. A moment of magnitude 14000 × 1400 N·mm is applied to the central node, with the moment direction specified as MX.

2.4 Mesh Convergence Analysis

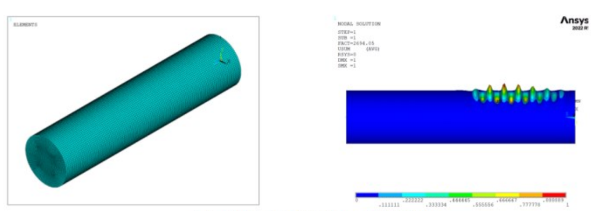
Different mesh densities were applied to the cylindrical surface and the end faces to investigate mesh convergence under varying densities. Four distinct mesh densities were selected for simulation (where hdenotes the element size on the end face). The first-order buckling modes obtained from the respective analyses are shown in Figure 1, and the corresponding calculation results are summarized in Table 1.



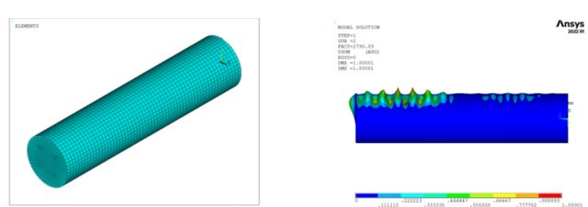
(a) Mesh element length is 12.5 mm and 1/96 mm.



(b) Mesh element length is 25 mm and 1/48 mm.



(c) Mesh element length is 50 mm and 1/24 mm.



(d) Mesh element length is 100 mm and 1/12 mm.

Figure 1 Finite element analysis results of buckling modes for varying mesh element sizes

Table 1 Buckling calculation results for varying mesh element sizes

Mesh Size on End Face (mm)	Mesh Size on Cylindrical Surface (mm)	Number of Elements	Buckling Factor
h/96	12.5	239616	2662.50
h/48	25	59904	2669.58
h/24	50	14976	2694.05
h/12	100	3744	2790.09

Based on the data provided in Table 1, Figure 2 is plotted.

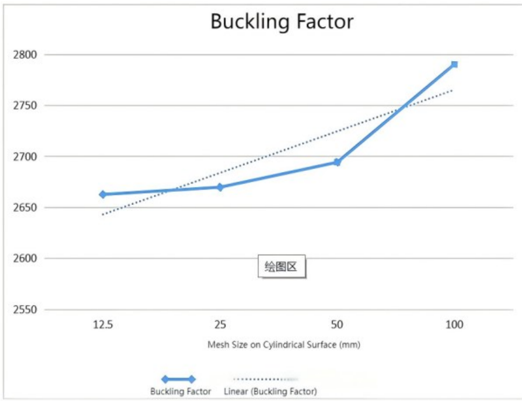


Figure 2 Buckling Coefficients of Thin-Walled Circular Tubes at Different Mesh Densities

The study of structural buckling modes under the four mesh densities revealed that the difference between the maximum and minimum buckling factors was 4.792%, with variations exceeding 1% among all four cases. This indicates insufficient mesh convergence. Therefore, the first three mesh densities were selected for comparative analysis. The results demonstrate a smooth curve under these conditions, with only minor differences observed in the buckling factors. After comprehensively considering computational cost and accuracy, the optimal performance was achieved with a mesh element length of 25 mm combined with h = 100 mm. Consequently, all subsequent analyses and calculations employed this mesh size to ensure the reliability and scientific validity of the research findings.

3 Parametric Analysis of the Influence of Pad Geometric Parameters on the Buckling Capacity of Thin-Walled Circular Tubes

3.1 Effect of Pad Length

Under the initial conditions, the pad length *a* was varied according to Table 2, and the first-order buckling modes of the thin-walled circular tubes were calculated.

Table 2 Geometric parameters of the thin-walled circular tube structure with variations

D(mm)	L(mm)	T(mm)	a(mm)	t(mm)	θ(º)
1400	6000	14	0	0	63.75
1400	6000	14	200	14	63.75
1400	6000	14	400	14	63.75
1400	6000	14	600	14	63.75
1400	6000	14	800	14	63.75
1400	6000	14	1000	14	63.75

Table 3 Relationship between the variation in pad length and the buckling factor

a(mm)	α	Buckling factor
0	0	2706.90
200	200/6000	2693.02
400	400/6000	2669.58
600	600/6000	2646.72
800	800/6000	2624.88
1000	1000/6000	2532.42

Based on the data in Table 3, Figure 3 is plotted. The buckling factor of the thin-walled circular tube gradually decreases as the relative pad length increases. This indicates that longer pads result in a lower buckling factor for the member and a higher probability of instability.

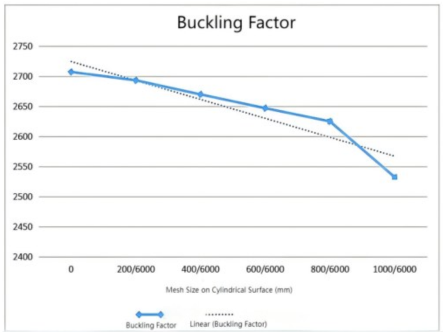


Figure 3 Relative Pad Length-Buckling Coefficient Curve

According to the data, it can be observed that when the pad length increases from 0 mm to 1000 mm, the buckling load decreases by 6.890%. This indicates that the pad design reduces the buckling capacity of the thin-walled circular tube. Moreover, as the pad length increases, the buckling capacity of the tube further decreases. Notably, these calculation results contradict the conventional understanding of pad design. Analysis suggests that the local thickness of the thin-walled circular tube changes after adding the pad, thereby affecting the overall structural stiffness and leading to the recurrence of wrinkling phenomena.

3.2 Effect of Pad Thickness

Under the initial conditions, the pad thickness twas varied according to Table 4, and the first-order buckling modes of the thin-walled circular tubes were calculated.

Table 4 Geometric parameters of the thin-walled circular tube structure with variations (Pad thickness)

D(mm)	L(mm)	T(mm)	a(mm)	t(mm)	θ(º)
1400	6000	14	0	0	0
1400	6000	14	400	14	63.75
1400	6000	14	400	28	63.75
1400	6000	14	400	42	63.75
1400	6000	14	400	56	63.75

Table 5 Relationship between the variation in pad thickness and the buckling factor

t(mm)	β	buckling factor
0	0	2706.90
14	1	2669.58
28	2	2652.25
42	3	2643.05
56	4	2668.49

Based on the data in Table 5 is plotted. As can be seen from Figure 4, with the increase of the relative pad thickness, the buckling factor of the thin-walled circular tube initially decreases and then increases, showing an overall decreasing trend.

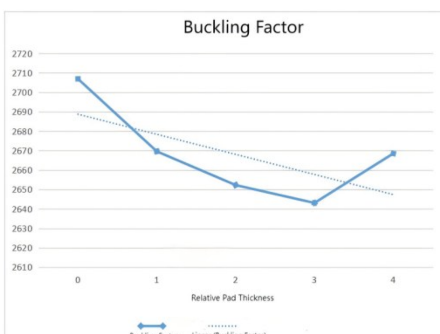


Figure 4 Relative Pad Thickness vs. Buckling Factor Curve

Based on the data, it can be observed that when the pad thickness increases from 0 mm to 56 mm, the buckling load generally decreases. This indicates that within a certain range, increasing the pad thickness does not enhance the buckling capacity of the thin-walled circular tube but rather has the opposite effect. This result remains inconsistent with conventional pad design principles, which can still be attributed to the alteration in the overall structural stiffness.

3.3 Effect of Pad Angle

Under the initial conditions, the pad angle θ was varied according to Table 6, and the first-order buckling modes of the thin-walled circular tubes were calculated.

Table 6 Geometric parameters of the thin-walled circular tube structure with variations (Pad angle)

D(mm)	L(mm)	T(mm)	a(mm)	t(mm)	θ(°)
1400	6000	14	400	14	45.00
1400	6000	14	400	14	52.50
1400	6000	14	400	14	63.75
1400	6000	14	400	14	71.25
1400	6000	14	400	14	75.00
1400	6000	14	400	14	90.00
1400	6000	14	400	14	101.25

Table 7 Relationship between the variation in pad angle and the buckling factor

θ(°)	buckling factor
45.00	2622.61
52.50	2666.50
63.75	2669.58
71.25	2672.37
75.00	2647.66
90.00	2660.29
101.25	2668.49

Based on the data in Table 7 and Figure 5 is plotted. With the increase of the pad angle θ, the buckling factor of the thin-walled circular tube initially increases, then decreases, and subsequently increases again, demonstrating an overall increasing trend.

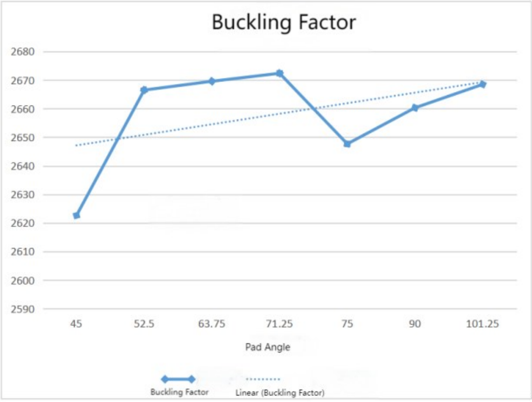


Figure 5 Angle-Buckling Coefficient Curve for the Base Plate

Based on the data, it can be observed that when the pad angle θ increases from 45° to 101.25°, the buckling load generally increases. This indicates that, within a certain range, increasing the pad angle has a beneficial effect on the buckling capacity of the thin-walled circular tube. This finding is consistent with conventional understanding of pad design.

4 Conclusion

This study employed the finite element method to simulate the static performance of thin-walled circular tubes strengthened with pads. By analyzing the geometric parameters of the thin-walled circular tubes, the influence of pad length, pad thickness, and pad angle on the buckling factor was investigated. The main conclusions are as follows:

(1) The pad length has a significant influence on the load-bearing capacity. The results show that a longer pad length leads to a lower load-bearing capacity of the thin-walled circular tube.

(2) As the pad thickness increases, the buckling factor of the thin-walled circular tube generally exhibits a decreasing trend.

(3) As the pad angle increases, the buckling factor of the thin-walled circular tube generally shows an increasing trend.

About the Author

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