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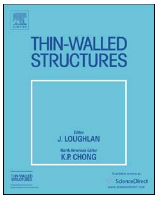

Full length article

Effects of ringed stiffener on the buckling behavior of cylindrical shells with cutout under axial compression: Experimental and numerical investigation

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ABSTRACT

In practical engineering, cutouts in thin-walled cylindrical shells are usually welded with ringed stiffeners for the purpose of connect and seal. In this paper, experimental and numerical studies have been conducted to investigate the effects of ringed stiffener on the buckling behavior of perforated cylindrical shells under axial compression. Three test specimens with ringed stiffener and three specimens without ringed stiffener are manufactured and tested. The mid-surface imperfections of all specimens are measured and introduced into the finite element model. The finite element method using static analysis with artificial damping is used to simulate the displacement controlled compression tests. Good agreement is found between the numerical and experimental results. It is found that the global buckling loads of perforated shells are improved by ringed stiffener. The larger the cutout size is, the more obvious improvement shows. In addition, effects of ringed stiffener on axial stiffness and imperfection sensitivity of perforated shells are studied in details. The relationship between ringed stiffener thickness and global buckling load of perforated shell is also discussed. Meanwhile, a critical thickness parameter k of approximately 15% is proposed.

1. Introduction

Thin-walled cylindrical shells are widely used in aerospace, petrochemical, nuclear engineering and other fields because of their efficient load carrying capacity [1–4]. Meanwhile, cutouts are often introduced into such structures for maintenance and inspection. The presence of cutouts in cylindrical shells can cause a destruction of structural continuity. Concretely, a significant reduction in axial load carrying capacity can been found in perforated cylindrical shells [5–7].

So far, a large number of investigations have been conducted on the buckling behavior of perforated cylindrical shells. Tennyson [8] performed an experimental study on the effects of circular cutout on the buckling load of cylindrical shells. Experimental studies were also carried out to clarify the influence of cutout on the buckling behavior of shells under axial compression [9,10]. Jullien and Limam [11] investigated the effects of square, rectangular, and circular cutouts on the buckling load of cylindrical shells. It was indicated that the buckling load is sensitive to the opening angle or circumferential size of the hole. Some researchers performed parametric studies to investigate the effects of cutout size, the length-to-diameter and the diameter-to-thickness ratios on critical buckling load [12,13]. In recent years, a detailed numerical study was performed to characterize the effects of cutout and initial geometric imperfections created using Single Perturbation Load Approach (SPLA) on the buckling loads of composite cylindrical shells [14]. Taheri [15] employed experimental and numerical procedures to investigate the effects of initial geometric imperfections on the buckling behavior of perforated composite cylinders. It was found that when the ratio of cutout diameter to shell radius is between 0.26 and 0.52, the load carrying capacity of cylindrical shell is mainly dominant by cutout size.

When the cutout is inevitable in these thin-walled structures, the reduced load carrying capacity may be insufficient to meet the requirements of structural safety. It is necessary to adopt a cutout-strengthening method to improve the axial load carrying capacity of perforated shells in these situations. Many researchers have investigated the buckling behavior of perforated plates with reinforcement [16–22]. Nevertheless, there are few studies about how to improve the load carrying capacity of perforated cylindrical shells under axial compression. Almorth [23] studied the influence of stringer stiffener on the buckling loads of cylindrical shells with square-shaped cutout. Toda [10] investigated the effects of annular plate on the critical buckling load of perforated shells. The results showed that the buckling load increased with the increase of reinforcement area in a certain range. Eggwertz [24] pointed out that the reinforcement may restore the load carrying capacity of perforated shells to a level equal to that of unperforated shells when the cutout size is small. Ghazijahani

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[25] found that the load carrying capacity of shells with rectangular cutout can be effectively raised by placing longitudinal stiffeners along the cutout long edge. Dimopoulos [26] studied the effectiveness of numerical methods proposed in EN1993-1.6 for the design of steel shells with reinforced cutout.

As aforementioned, some researchers investigated the effects of placing longitudinal stiffeners or annular plates around cutouts on the load carrying capacity of perforated shells under axial compression. However, in practical applications, especially in the field of nuclear engineering, the cutouts in thin-walled cylindrical shells are often welded with inserted ringed stiffeners for the purpose of connect and seal. To the authors' best knowledge, there is little published work regarding experimental evaluation on the effects of ringed stiffener on the buckling behavior of perforated cylindrical shells subjected to axial compression. Therefore, in this paper, the influence of ringed stiffener on load carrying capacity and buckling behavior of perforated cylindrical shells are investigated by employing experimental and numerical techniques. This paper is organized as follows: the buckling tests of six specimens under axial compression is introduced in Section 2. The parameters of finite element analysis (FEA) are given in Section 3. In Section 4, the results of numerical analysis and buckling tests are firstly compared and discussed, after that, the effects of ringed stiffener on axial stiffness and imperfection sensitivity of perforated shells are investigated. In addition, the relationship between ringed stiffener thickness and load carrying capacity of perforated cylindrical shell is also discussed. Finally, the conclusions drawn from this study is presented in Section 5.

2. Experimental study

2.1. Test specimen

In this experimental work, six perforated cylindrical shells are manufactured and tested. Three test specimens without ringed stiffener are labeled as 2-1, 2-2 and 2-3. The other three specimens are perforated shells with ringed stiffener and are labeled as 3-1, 3-2 and 3-3. The ringed stiffener is welded to the shell, as shown in Fig. 1. The geometry data of six specimens are listed in Table 1. It should be noted that the diameter and thickness of ringed stiffeners are determined based on the Chinese Standard HG/T 20615-2009 [27]. The outer diameters of ringed stiffeners in specimen 3-1, 3-2 and 3-3 are the same as the cutout diameters of specimen 2-1, 2-2 and 2-3, respectively.

Both the shell and the ringed stiffener are made of mild steel. A tensile test is conducted to obtain the material properties according to the Chinese Standard GB/T228.1-2010 [28]. The Young's modulus, Poisson ratio and yield strength of material are tabulated in Table 2.

In order to achieve clamped boundary conditions, both ends of the test specimen are welded into the 5 mm depth grooves created on the metal rings. The height of each ring is 20 mm, as shown in Fig. 2. Because of the specimen overall height is 600 mm, the free height of specimen excluding the metal ring is 560 mm.

Table 1
The geometry data of six specimens.

	2-1	2-2	2-3	3-1	3-2	3-3
Diameter, *D* [mm]	1000					
Height, *H* [mm]	600					
Thickness, *T* [mm]	1.5					
Cutout diameter, *d* [mm]	88.9	114.3	139.7	88.9	114.3	139.7
Ringed stiffener thickness, *t* [mm]	–	–	–	4.7	5.15	5.1
Cutout height, *h* [mm]	300					
Ringed stiffener length, *l* [mm]	50					

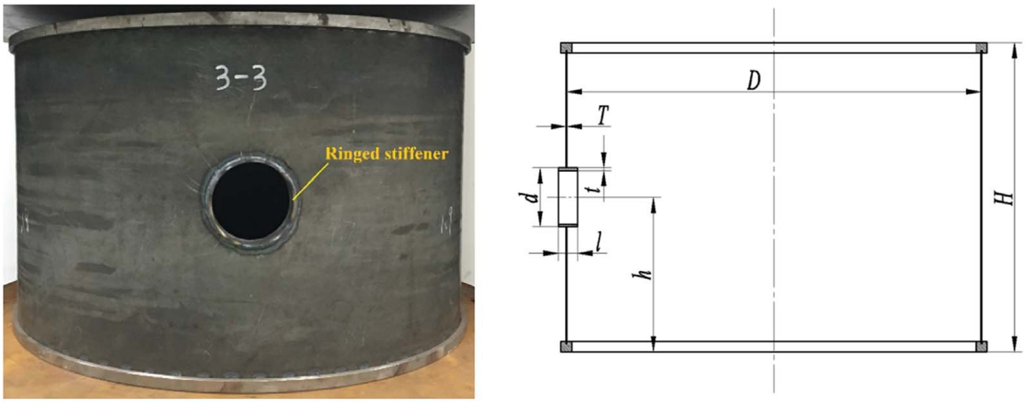
Table 2
Material properties.

Young’s modulus [GPa]	Poisson ratio	Yield strength [MPa]
202	0.3	338.3

2.2. Test rig

The buckling tests of six steel specimens are performed in the axial compression buckling test rig, as shown in Fig. 3. The test rig has the functions of mid-surface imperfections measurement, axial hydraulic loading and real-time acquisition of axial pressure signals. Characteristics of the test rig are given in Table 3.

The mid-surface imperfections of six specimens are measured by the geometric imperfection measuring system. This system is mainly composed of self-aligning ball bearings, laser displacement sensor (Fig. 4a), ball screw, rotating frame and two stepper motors. The circumferential rotation and axial translation of displacement sensor are realized by the rotating frame and ball screw respectively, so the mid-surface imperfections of six specimens can be scanned and measured. The axial compression load of test rig is provided by hydraulic loading system. And in order to prepare the static test condition as much as possible, the axial load is applied using displacement control with a constant speed of 1 mm/min, which is the minimum speed that the test rig can achieve. During the buckling test, three processes of the pressure head can be switched automatically by the control cabinet, including fast down, slow press and fast return. What’s more, the real-time acquisition of axial pressure signal is realized by the pressure sensor cooperating with the data acquisition and analysis system, DH5932 (Fig. 4b).



（a）Real structure （b）Struture’s geometry

Fig. 1. Test specimen.