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Effect of shape imperfection on the buckling of large-scale thin-walled ellipsoidal head in steel nuclear containment

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ABSTRACT

Buckling is a failure mode of a large-scale thin-walled ellipsoidal head for a cylindrical steel containment vessel, which is widely used in nuclear power plants such as AP1000 and CAP1400. Manufacturing processes always induce shape imperfections in large-scale thin-walled ellipsoidal heads. However, the study on the effect of shape imperfections on the buckling of a large-scale thin-walled ellipsoidal head subjected to internal pressure is still lacking. In this work, we first used a 3D laser scanner to measure the overall shape of the ellipsoidal head which has a diameter of 5000 mm, a radius-to-height ratio of 2.0 and a thickness of 5.5 mm. On the basis of the measured overall shape, shape imperfections were determined, and an equation was proposed to quantitatively characterize bulging of weld in the knuckle. Secondly, the measured overall shape and the equation were used to develop FEA models with shape imperfections. Buckling pressures were predicted by using nonlinear FEA. Good agreement between the predictions of the FEA models with shape imperfections indicates that bulging of weld has a considerable effect on buckling pressure. Thirdly, a buckling experiment was performed on the ellipsoidal head and buckling behavior was obtained. The experimental results show that all the buckles occurred at the bulgings of welds. The agreement between the experimental results and the predictions based on the models with shape imperfections is good. At last, FEA models, including different bulging heights of welds characterized by the equation, were established to perform an imperfection sensitivity analysis. Thin-walled ellipsoidal heads subjected to internal pressure demonstrate a significant sensitivity to the bulging height of weld in the knuckle.

1. Introduction

Cylindrical steel containment vessels are widely used in nuclear power plants such as AP1000 and CAP1400. A large-scale thin-walled ellipsoidal head is an integral component of a cylindrical steel containment vessel, which accommodates internal pressure and limits the release of radioactive materials due to a loss of coolant accident [1–3]. Hence, internal pressure is a critical load considered in the design of an ellipsoidal head. Although an ellipsoidal head is subjected to internal pressure, the knuckle of an ellipsoidal head may be in compressive circumferential stress state. Thus, buckling is a potential failure mode for an ellipsoidal head under internal pressure.

Large-scale ellipsoidal heads are usually constructed from several plates. The plates are formed by pressing process and then welded together. Forming and welding processes will inevitably result in shape imperfections, such as deviation along a meridional line, out of roundness and bulging of weld. 3D laser canners can measure the shape of a structure more completely and conveniently, compared to a coordinate measuring machine or other traditional measuring technique. Kainat et al. [4] investigated the geometric imperfections of steel pipes by using 3D surface scanners. Wang et al. [5] used a 3D scanning system to measure the shapes of 451.5 mm diameter torispherical heads and determined shape imperfections. Rotter [6] and Teng [7] proposed shape functions to characterize shape imperfections of cylindrical shells. However, the study on the characterization of shape imperfections of large-scale ellipsoidal heads is still lacking.

Many researchers [5,8–10] focused their attentions on the effect of shape imperfections on the buckling of torispherical or ellipsoidal heads subjected to external pressure. There was limited literature on the effect of shape imperfections on the buckling of internally-pressurized ellipsoidal heads. Sorić [11] performed a nonlinear elastic stability analysis of imperfect torispherical shells under internal pressure. The investigation of imperfection sensitivity is concerned with imperfections affine to the first buckling mode at bifurcation points of a perfect shell.

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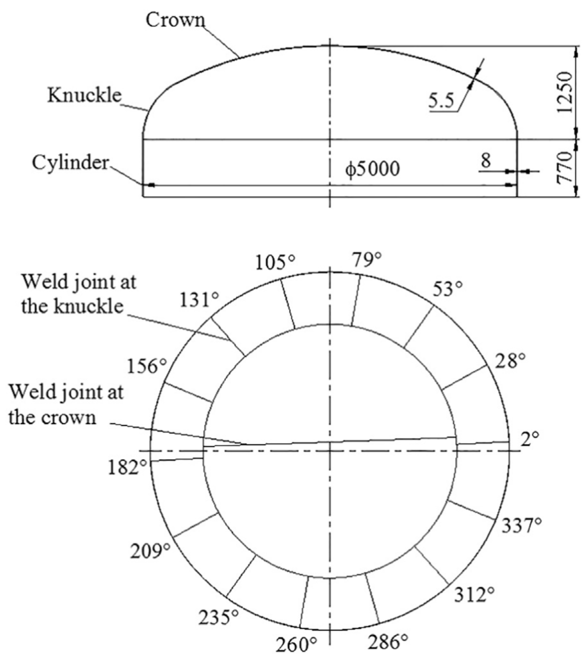

Fig. 1. Geometry of the ellipsoidal head (in mm).

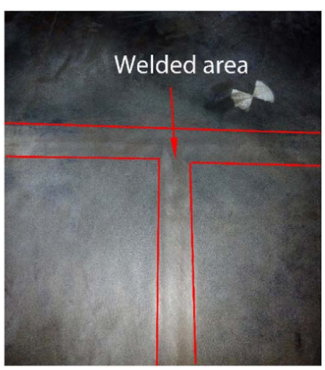

Fig. 2. Photograph of welded area.

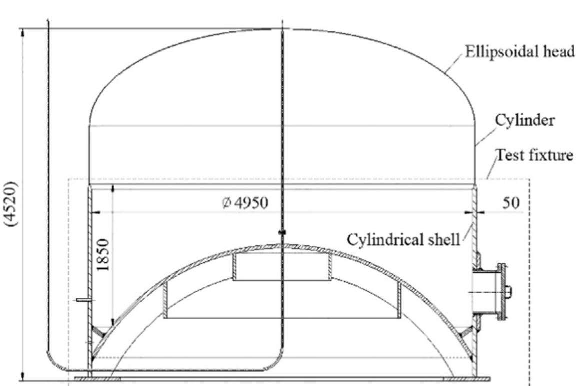

Fig. 3. Geometry of the test vessel (in mm).

Wan [12] researched the influence of initial shape imperfections on localized elastic-plastic buckling of a torispherical head under internal pressure. The localized initial shape imperfection was generated by defining the initial displacement of some nodes in the knuckle. However, these imperfections were not determined by measurements and did not exactly characterize those of engineering structures.

In addition, there have not been any buckling experiments conducted on large-scale ellipsoidal heads under internal pressure. Miller et al. [13] performed the internal pressurized buckling tests of two torispherical heads with a diameters of 4876.8 mm, and the two heads tested by Miller were approximate 2:1 ellipsoidal heads. A buckling test of a 4797 mm diameter ellipsoidal head subjected to internal pressure was investigated by Li et al. recently [14,15].

Fig. 4. View of the ellipsoidal head during test.

Table 1
Geometry measurements of the ellipsoidal head.

D_o (mm)	h_o (mm)	t (mm)		
		Crown	Knuckle	Cylinder
5013.7	1284.3	5.8	6.1	8.6

In this paper, the overall shape of a large-scale thin-walled ellipsoidal head was measured by using a 3D laser scanner. An equation was proposed to quantitatively characterize the bulging of welds. To investigate the effect of the bulging of welds on buckling pressure, the measured shape and the equation were used to develop the FEA models with shape imperfections. Buckling pressures were predicted by using FEA involving both geometric and material nonlinearity. An experiment was performed to investigate the buckling behavior of the ellipsoidal head and verify the validity of the FEA models. Finally, FEA models considering different bulging heights of welds were developed to investigate the imperfection sensitivity of the internally-pressurized ellipsoidal head.

2. Shape imperfections

2.1. Shape measurement

Fig. 1 shows the geometry of the ellipsoidal head which is attached to a cylinder. The crown is welded by two plates and then formed by cold pressing to the crown radius (4458.6 mm). The knuckle is constructed from fourteen petals which are formed by cold pressing in a die and then welded together (the knuckle radius is 855.5 mm). The welding process is shielded metal-arc welding. The class of welding material is E9018-G-H4. Metal oxide on and nearby the groove was cleaned before welding. The temperature of welding parts was preheated above 25 °C. After welding, the excess (weld reinforcement, welding splash, coating, etc.) was removed. The welded area is shown in Fig. 2.

A test vessel (Fig. 3) was designed to perform the buckling experiment of the ellipsoidal head. The test vessel includes the ellipsoidal head, the cylinder and a test fixture. The cylinder was welded to the test fixture which is the same as that of the test vessel designed in literature [14,15]. Design pressure of the test fixture is taken as plastic collapse pressure of the ellipsoidal head. This provides a substantial margin of safety which permitted testing the ellipsoidal head to burst. A stress