Thin-Walled Structures 113 (2017) 104–110

Contents lists available at ScienceDirect

Thin–Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Imperfection sensitivity of externally-pressurized, thin-walled, torispherical-head buckling

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ARTICLE INFO

Keywords:
Thin-walled
Torispherical head
Water heater tank
Buckling
Imperfection sensitivity
Finite element analysis

ABSTRACT

The bottom head in the residential electric water heater tank is an externally-pressurized, thin-walled, torispherical structure. In this paper, the buckling behavior of the bottom head was studied by experimental and finite element analysis (FEA) methods. The shapes of four randomly selected water heater tanks were measured by Computer Aided Inspection (CAI), and hydrostatic tests and strain measurements were performed. The buckling simulations of the tested tanks were carried out by finite element method, and the obtained results were in good agreement with the experimental data. Two parameters, contact imperfection ratio, R_{imc}, and geometry imperfection ratio, R_{img}, were used to quantitatively characterize the magnitudes of the main imperfections in the water heater tank manufacturing process. FEA models, including both contact and geometry imperfections, were used to investigate the buckling pressure of the bottom head. The results show that the geometry imperfection, within the range of ASME Code VIII-2 requirements, has a greater effect on the buckling pressure than the contact imperfection. The obtained curves of buckling pressure versus imperfections can provide guidance for water heater tank design and manufacture.

1. Introduction

The residential electric water heater tank is a thin-walled pressurized element with a maximum operating pressure of 1.034 MPa and a maximum operating temperature of 75 °C, which typically consists of two torispherical heads and a shell. The bottom head and shell are connected using a single fillet lap weld where the bottom head is not only the end closure of the tank, but also the tank support, allowing the tank to be oriented in the vertical position, as shown in Fig. 1. When a water heater is in operation, the bottom head is under the influence of external pressure on the convex surface. Buckling of the bottom is, therefore, a potential failure mode to be prevented in the design.

The investigations of torispherical head buckling under external pressure have been performed in the past several decades. Washington et al. [1] presented an early study on the buckling of externally pressurized torispheres, where eighteen pressure vessel heads having nine different geometries and made from two different steels were subjected to monotonically increasing external pressure until collapse occurred. Galletly [2] used numerical analyses to investigate the buckling of shallow dished ends under external pressure. The results showed that the application of BS 5500 to the design of shallow steel torispheres subjected to external pressure can result in safety factors which are lower than the expected 1.5. Blachut [3,4] also observed that the radius of the knuckle in the torisphere needs to be considered in the design, and torispheres with a knuckle radius of approximately equal to 6% of diameter might collapse well below the recommended design curve. It is well known that imperfections have a great effect on the buckling of the thin-walled shell under external pressure. Lu et al. [5] performed a systematic numerical investigation of the nonlinear elastic and elastic-plastic load-carrying behavior and imperfection sensitivity of torispherical pressure heads under uniform external pressure. The authors found that thinner shells are more sensitive to the value of the yield stress and the magnitude of initial geometric imperfections, but their load-carrying capacity, relative to the elastic bifurcation pressure, may also be significantly higher than that of thicker shells. Blachut and Galletly [6] investigated the influence of localized shape imperfections on the elastic buckling of torispheres by the finite element method and experiment, and the validity of the lower-bound curve of the collapse pressure versus size of the imperfection was confirmed experimentally. The authors also found that the predicted buckling strength was not influenced by the location of the flattening. Blachut and Jaiswal [7] imposed different initial geometric imperfections on perfect shells to study the reduction of the load-carrying capacity. Results show that the buckling strength of torispheres could be strongly affected by imperfections, but reduction of its magnitude was dependent on the choice of imperfection shape and, more importantly, on the imperfection's

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http://dx.doi.org/10.1016/j.tws.2017.01.018
Received 25 October 2016; Received in revised form 5 January 2017; Accepted 13 January 2017
0263-8231/

Nomenclature

D_i	inside diameter of the bottom head
e	true strain of the steel
L_c	outside circumference of the bottom head
L_{im}	imperfection width of the contact between the shell and the bottom head in the circumferential direction of a tank
P_{buckle}	buckling pressure
P_{buckle}^{FEA}	buckling pressure from finite element analysis
P_{buckle}^{test}	buckling pressure from a test
R_{imc}	ratio of the contact imperfection width to the outside circumference of the bottom head
R_{img}	ratio of the maximum geometry deviation to the inside diameter of the bottom head
R_s	inside crown radius of the bottom head
s	true stress of the steel
t	thickness of the bottom head
x	arc length away from the bottom head end in the meridional direction
δ_0	maximum geometry deviation of the bottom head from the perfect shape

location. Wunderlich et al. [8] pointed out that the details like boundary conditions, material properties, and imperfections should be taken into account when the design rules for the shell under external pressure were developed. During the assembly process of the bottom head and the shell in a water heater tank, the bottom head is inserted into the shell, and then welded to the shell end. Therefore, a flare is formed at the shell end after the assembly process, and there is a contact region between the bottom head and the shell, as shown in Fig. 1. Wang et al. [9] have studied the effect of imperfections induced by contact nonuniformities between the bottom head and shell on the buckling of the structure and found that the buckling pressure of the bottom head perfectly contacting the shell is 6.88% higher than the case with no shell contact. After fabrication, the deviation of the tank from the perfect shape is inevitable, so the buckling strength of the bottom head containing both geometry and contact imperfections needs further investigation.

In this paper, four water heater tanks were randomly selected from a large number of the products, and the hydrostatic test was performed to study the buckling strength of the bottom heads. To evaluate the geometry imperfection sensitivity of the bottom head buckling, prior to testing, the shapes of the test tanks were measured by the Computer Aided Inspection (CAI) technique. Finite element analysis (FEA) based on the measurement data was performed to confirm the finite element models. Then the buckling behavior considering both geometry and contact imperfections was investigated. The obtained results can provide guidance for the water heater tank design and manufacture.

2. The hydrostatic test of the water heater tank

2.1. Test procedure

The shape measurements of four test tanks were made on the outside surface of each tank using Computer Aided Inspection (CAI) [10]. CAI is a new technology that enables one to develop a comparison of a physical part to a 3D CAD model. This process is faster and more complete than using a Coordinate Measuring Machine (CMM) or other more traditional methods. Each tank was scanned with a scanner, model Comet L3D5M, manufactured by Steinbichler, which had an accuracy of ± 0.0254 mm. The scanning system is shown in Fig. 2. The procedure for scanning the tanks is the following:

1. The whole outside surface of a tank is cleaned with a denatured alcohol;
2. The tank is coated with either a flat white paint;
3. Removable circular stickers are placed over the tank surfaces to act as target tie-points for the scanning process;
4. The scanner is calibrated and then the tank is scanned;
5. When the scans are completed, then scanning software optimizes the

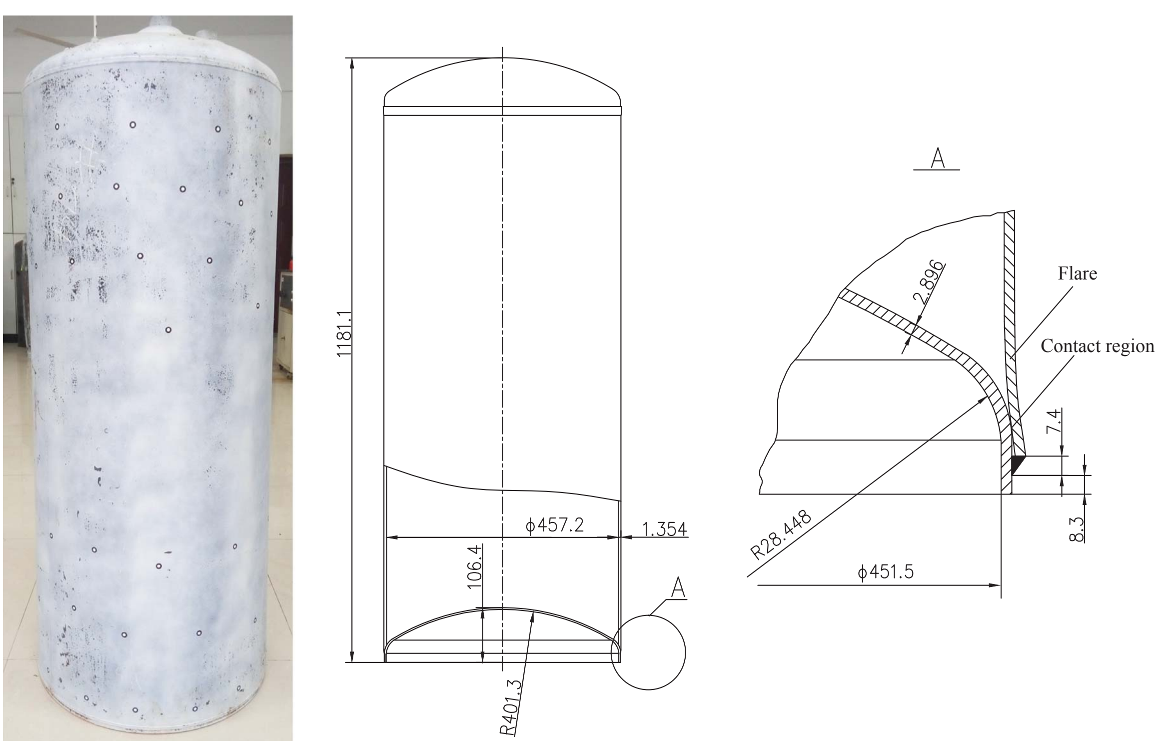

Fig. 1. The structure and the dimensions of the water heater tank (in mm's).