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Buckling of cylindrical stainless-steel tubes subjected to external pressure at extremely high temperatures

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ABSTRACT

This study aims to experimentally investigate the buckling behaviors of stainless steel cylindrical tubes subjected to external pressure at extremely high temperatures. Buckling experiments were conducted on specimens of two different buckling modes for a wide range of pressures, specifically, from 200 to 1000 kPa in gauge pressure. The buckling temperature was measured as a function of the external pressure to examine the relationship between the buckling temperature and the external pressure. Moreover, the effect of the tube dimension (radius-to-thickness ratio) on the buckling temperature was investigated for a wide range of radius-to-thickness ratios, specifically, from 10 to 56. The buckling temperature was proportional to the external pressure and to the radius-to-thickness ratio. The measured buckling temperatures were compared with the theoretical predictions obtained from several conventional buckling models. The difference in the buckling temperatures between the experimental results and the theoretical predictions was discussed by considering the creep effect, geometrical imperfections, and a temperature dependent material property. Additionally, the buckling deformation of the stainless steel tube columns was recorded with a high-speed camera.

1. Introduction

Cylindrical tubes have been widely used in various piping systems in several industries, such as the building, power-plant, and large-machinery industries. Typically, tubes are utilized to transport fluids (liquid or gas); therefore, ensuring the stability of the tubes is a significant issue in preventing leakage of fluids—occasionally toxic and harmful materials—induced by failure of the tubes. Buckling is an important failure mode because it occurs below the ultimate strength of the materials. It is well known that that the prevention of buckling is the primary design problem because buckling leads to undesirable configurations, such as collapse, and finally reduces the structural integrity [1]. For this reason, several studies on buckling failure under various conditions have been conducted for diverse tube columns. Because buckling is an instability that leads to a failure of plates and shells, it has been analytically examined for various shapes under diverse loads and for various combinations thereof [2,3]. Windenburg and Trilling summarized and discussed theoretical models for buckling collapse of thin-walled cylinders subjected to external pressure [4]. The collapsing pressures of the tubes, which were estimated via various formulas, were compared for three different tubes; tubes of infinite length, tubes of finite length with uniform radial pressure only, and tubes of finite length with both uniform radial and axial pressures.

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Diverse studies have been conducted on cylindrical tubes and cylindrical shells under external pressure conditions [5–13]. Corona and Kyriakides examined the effects of cyclic bending and external pressure on the rate of accumulation of ovalization and on the onset of instability for cylindrical tubes at room temperatures [7]. Park and Kyriakides experimentally showed that the local collapse resistance of long cylinders under external pressure is reduced by local dents. The collapse pressures decreased by as much as 50% for an ovality of approximately 10% [8]. In other studies, the effects of geometrical imperfections on buckling collapse under external pressure have been investigated for tube columns [9–13]. Lo Frano and Forasassi showed that the ovality and the eccentricity of the tube reduced the buckling pressure of the A-316 stainless steel and of a Ni–Cr alloy (Inconel 690). Additionally, they compared the experimental results with numerical estimations of the buckling pressure for various diameter-to-thickness ratio values [11,12]. Fatemi et al. performed buckling tests for thin-walled shell structure with very large radius to thickness ratios of 500 and 600 to examine the effect of welding process-induced geometric imperfections on the buckling resistance. They compared the initial buckling pressure and the collapse pressure between geometrically perfect shells and imperfect shells. The initial buckling pressure and collapse pressure decreased by up to approximately 44%. However, the welding caused the stiffening influence so that the collapse pressure rather increased to approximately 9% on average [13]. Recently, Ge et al. conducted the analysis of the buckling and post-buckling of a subsea separator under external pressures numerically and experimentally. They showed the asymmetrical buckling deformation. The influences of length to diameter ratio on the critical buckling pressure was examined in this paper. [14].

Although numerous research works have been conducted on buckling for different applications, studies on buckling at elevated temperatures are relatively few [15–18]. More specifically, experimental works on the buckling of tube columns subjected to loads in the radial direction at extremely high temperatures are barely available. The Okamoto research group has experimentally investigated the buckling and the creep buckling behaviors of stainless-steel plates and cylindrical tubes [19–23]. The relation between the compressive load and the buckling temperature was examined for a slender plate with rectangular cross-sections for the temperature range of 25 to 1200 °C [19–21]. Moreover, the creep buckling failure time was measured, and the time evolution of the creep buckling deformation was quantitatively obtained for the same plate column [22]. Furthermore, Jo et al. measured the buckling temperature of thin cylindrical metal tubes under external pressure at extremely high temperatures [23]. An extensive parametric study was conducted, and the shapes of the cylindrical tube, which had been buckled in experiments, were compared to the numerical predictions. However, it is obvious that more experimental studies are necessary to understand the characteristics of the buckling of thin tube columns and to enhance the structural integrity of pipes and tubes in several applications, such as in nuclear power plants and in chemical plants.

In this study, hence, the buckling behaviors of the cylindrical stainless steel tube column was investigated under external pressure at extremely high temperatures. Diverse parameters were examined to understand relationships of the buckling temperature with the external pressure and the tube dimensions. In addition, the experimental measurements were compared with results from conventional theoretical formulas on buckling temperatures. Finally, the buckling collapse was visualized using a high-speed camera, and the deformation of the cylindrical tube was quantitatively obtained through image processing.

2. Experimental methods

Fig. 1 shows an image of a tube column that was made of Type 304 stainless steel (SUS304). The tube column had three different diameters, which were named Tube 1, Tube 2, and Tube 3 according to the order of their diameter. The inner diameters of Tubes 1, 2, and 3 were 13.0, 18.4, and 22.1 mm, respectively. The main test section (middle part) of the tube column was thinner than the two end sections to increase the temperature via the Joule heating method. The length of the middle part was 100 mm, and the thickness varied from 0.2 to 0.7 mm. Table 1 summarizes the dimensional information for all tube columns that were tested in the present

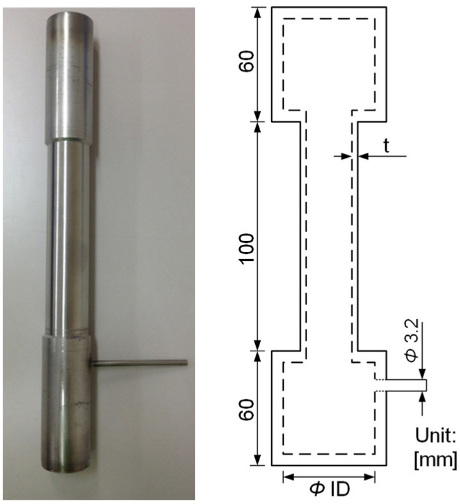

Fig. 1. Image of a tube column.