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Review

Recent progresses in experimental investigation and finite element analysis of ratcheting in pressurized piping

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A B S T R A C T

This article presents an overview of recent progresses in experimental investigation and finite element analysis (FEA) of ratcheting behavior of pressurized piping. Ratcheting, namely the cyclic accumulation of plastic deformation, occurs when the structures are subjected to a primary load with a secondary cyclic load if the applied loads are high enough to make the structures yield. Typical piping structures including straight pipes, elbow pipes and piping joints have been investigated experimentally under mechanical or thermal cyclic loading. Finite element analyses with several well-developed constitutive models implemented in the commercial software ANSYS and ABAQUS have been conducted to simulate and predict the ratcheting behavior of pressurized piping. Based on such experimental and FEA research, ratcheting boundaries have been determined with the final aim of aiding the safety design and assessment of engineering piping structures. Some suggestions for structure ratcheting study are proposed.

1. Introduction

In the materials or structures subjected to a cyclic stressing with non-zero mean stress, a cyclic accumulation of inelastic deformation will occur if the applied stress is high enough (ensuring that a yielding occurs), which is called ratcheting or ratcheting effect (some researchers called it cyclic creep too). Structural ratcheting is proposed by Hübel [1]. Structural ratcheting can occur owing to inelastic material behavior under cyclic loading, but more sophisticated than material ratcheting for its inhomogeneous multiaxal stress state due to various load combinations.

Pressurized piping as the most basic structures in chemical industries and nuclear power plants are subjected to variable mechanical and thermal loads which often have a cyclic nature. Let us consider a simple straight pipe that is under a constant pressure and suffers cyclic thermal gradient in the radial direction. In this case, the pipe can be viewed as subjected to a primary load in the axial and circumferential directions due to the constant pressure and a secondary cyclic bending moment caused by the cyclic thermal gradient. If the loads are high enough to make the structure yield, the plastic deformation may be accumulated cycle-by-cycle until the plastic collapse of the structure occurs. This phenomenon is known as ratcheting, i.e. structural ratcheting. Similar to other damage mechanisms such as fatigue and creep, ratcheting has also been considered in many design criteria for engineering components and structures, including ASME Code Section III [2], KTA [3], EN13445 [4], R5 [5] and RCC-MR [6]. These criteria require the structures to remain below the defined ratcheting boundaries where elastic or plastic shakedown occurs [7]. However, current methods to determine the ratcheting boundaries can be too conservative, or sometimes non-conservative. It is therefore of great significance to investigate the ratcheting behavior of such structures and predict it with sound accuracy, which has already been concerned during the last two decades.

So far, several scholars have reviewed research work on ratcheting of materials and structures. Ohno [8] and Kang [9] have reviewed the progresses in ratcheting research for various materials with emphasis on phenomenon observation and constitutive modeling obtained before 1997 and 2008, respectively. In addition, several components of consistent tangent modulus of several constitutive models were discussed by Kang [9]. Abdel-Karim [7] reviewed the literature on shakedown problems of various structures including 4-bar structure, beam, rotating disc, thin infinite plate, infinite plate with a central hole, and tube under internal pressure and variable temperature. According to Abdel-Karim [7], determination of ratcheting boundaries were limited mostly to the

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simple linear kinematic hardening rule (LKH) of Prager and the nonlinear kinematic hardening of Armstrong–Frederick (AF). The advanced kinematic hardening rules introduced in Ref. [7] had been reported to yield more accurate simulation of ratcheting behavior [8,9]. Being different from these review papers, recent experimental and numerical progresses of the structural ratcheting for various piping components are mainly reviewed in this paper. The process of AF type constitutive models implemented into ANSYS software is detailedly reviewed. The fourth-rank constitutive parameters $\mathbf{H}_{n+1}^{(i)}$ of consistent tangent modulus for AF type constitutive models are derived. The predictions of structural ratcheting with advanced kinematic hardening rules are discussed. The ratcheting boundary determinations for piping components are reviewed.

In the present article, Section 2 summarizes the experimental observation of ratcheting behavior of pressurized straight pipes, elbow pipes, tee pipes and cylinders with lateral nozzles, which are subjected to the constant internal pressure and quasi-static cyclic loading or dynamic loading. In Section 3, the methods of finite element implementation of constitutive models with advanced kinematic hardening rules are briefly reviewed. Finite element analyses (FEA) of ratcheting behavior of pressurized piping are evaluated in Section 4. In Section 5, ratcheting boundaries determined by such FEA are commented. Finally, some suggestions for further studies are proposed as a conclusion of the review.

2. Experimental observation

Ratcheting effect, namely the cyclic accumulation of secondary plastic deformation, occurs when the structures are subjected to a primary load with a secondary cyclic load if the applied loads are high enough to make the structures yield. Considering that the yielding of structures essentially originates from the yielding of materials in some local parts where stress level is high, the accumulation of plastic deformation of the structures can be represented by the local ratcheting strain in the following three forms, which is similar to the case of ratcheting tests for materials,

$$\varepsilon_r = \frac{1}{2}(\varepsilon_{max}+\varepsilon_{\min}) \quad (1)$$

or

$$\varepsilon_r = \varepsilon_{\max} \quad (2)$$

or

$$\varepsilon_r = \varepsilon_{\min} \quad (3)$$

where, $\varepsilon_{\max}$ and $\varepsilon_{\min}$ are the maximum and minimum plastic engineering strain in a cycle. To evaluate the evolution of ratcheting strain, ratcheting strain rate is widely used, which is defined as the increment of ratcheting strain during each cycle.

So far, ratcheting behaviors of various pressurized piping structures of different materials have been extensively studied in the last several decades as shown in Table 1. These structures include straight pipes and elbow pipes as the typical ones, as well as other structures such as tee and lateral nozzle. Internal pressure was the common constant load exerted on these structures. Cyclic loadings in two control modes, displacement control and load control were mainly applied in these tests. For displacement control, cyclic loading was applied in the controlled waveform of displacement or rotation, while for loading control cyclic loading was applied in the controlled waveform of force. The detailed descriptions of the ratcheting behavior for each type of piping structure under different control modes are presented as follows.

2.1. Ratcheting behavior of straight pipe

The experimental modes to apply cyclic loads to pressurized straight pipes mainly contain three-point bending [10],

Table 1
Review of published literatures on ratcheting investigation of pressurized piping structures.

Scholar	Material	Structural type	Constant loading	Cyclic loading	Control mode
Fujiwaka et al. [33,109]	Carbon steel: SA106 GrA Stainless steel: SA312TP304	Straight pipe Elbow pipe/Tee	IP IP	Static displacement cyclic loading Seismic load	Displacement control
Gau [14]	Carbon steel 304 stainless steel	Straight pipe	IP	Displacement-controlled cyclic bending load	Displacement control
Moreton et al. [20,25,26]	Mild steel Stainless steel	Straight pipe Elbow pipe	IP	Fully reversed cyclic bending moments	Load control
Corona and Kyriakides [30]	Aluminum	Straight pipe	IP	Cyclic bending load	Load control
Kulkarni et al. [12,13]	SA333 Gr.6 carbon steel SS304 stainless steel.	Straight pipe Elbow pipe	IP	Cyclic bending load Shake table	Load control
Chen et al. [28,29,49,50,52,123]	Low carbon steel	Straight pipe Elbow pipe	IP	Reversed bending load	Load control
Rahman et al. [16,17]	Alloy steel 4130 SS304L	Straight pipe Elbow pipe	IP	Cyclic rotation Opening–closing cyclic loading	Rotation control Displacement control Force control
Yoshida et al. [22]	Carbon steel	Straight pipe	IP	Cyclic axial load	Load control
Guionnet et al. [23,92]	Austenitic stainless steel (17-12SPH)	Tubular specimen	Tensile stress	Cyclic torsional loading	Load control
Rider et al. [24]	304S11 stainless steel En6 Low carbon steel	Thin-walled cylinders	IP	Cyclic tensile loading	Load control
Ichihashi [34]	Stainless steel Low carbon steel	Piping components	IP	Quasi-static cyclic loading Dynamic cyclic loading Shaking table	Under sinusoidal deflection control Under inertial force due to seismic excitation and sinusoidal excitation
Igari et al. [11]	316FR	Straight pipe	IP	Cyclic moment loading	Displacement control
Acker et al. [45]	Non indicated	Elbow pipe	IP	In-plane bending	Displacement control
Guionnet [23,92]	Austenitic stainless steel	Tube	Tensile stress	Cyclic torsional loading	Load control

Note: Internal pressure is abbreviated to IP.