# ISSUES RELATED TO RATCHETING IN PIPING COMPONENTS

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## Abstract

Material and piping component test data involving ratcheting are discussed in regards to the phenomenon of shakedown. The data set studied indicates that the general belief about the occurrence of shakedown after a few cycles of ratcheting needs revisiting. Areas in the ASME Boiler and Pressure Vessels Code, Section III, Division 1, which address design issues related to ratcheting and shakedown, are discussed. A systematic methodology to understand the influence of ratcheting on fatigue failure and to incorporate ratcheting into the design of piping components is presented.

## Introduction

Ratcheting is defined as the accumulation of deformation or strain with cycles. When a piping component is subjected to a force-controlled cycle, deformation may accumulate in the component (global ratcheting), or strain may accumulate at peak stress locations (local ratcheting). It has been demonstrated experimentally that ratcheting may cause structural instability (global failure) or premature fatigue failure (local failure) of a component (EPRI, 1992). The ratcheting phenomenon has been known to researchers from the turn of the twentieth century (Bairstow, 1911), but the implication of the phenomenon to safe design of a structure has yet to be fully explored. The main reason for this is the widespread belief in the phenomenon of shakedown, which is defined as the complete cessation of ratcheting after a few cycles.

Pioneering works of Parkes (1954), Miller (1959), Edmunds and Beer (1961) and Bree (1967) discussed various aspects of ratcheting and shakedown in structural components subjected to thermal cycles. Bree (1967) proposed a stress diagram to identify stresses that induce ratcheting, shakedown, plastic cycling and elastic cycling. This diagram, well-known as the Bree diagram, has been incorporated into the ASME Boiler and Pressure Vessel Code (ASME, 1998a) as a design approach for limiting strain accumulation in cylinders subjected to cyclic thermal loading under sustained primary stresses. The Bree diagram has been developed using uniaxial analysis with elastic-perfectly plastic material. Most structures, in reality, are subjected to multiaxial stresses and their ratcheting responses cannot be predicted by elastic-perfectly plastic material model. Hassan and Kyriakides (1994), Corona et al. (1996) and Bari and Hassan (1999) have demonstrated that even a sophisticated constitutive model fails to predict multiaxial ratcheting responses. In addition, to the author’s knowledge, there is no experimental evidence of the occurrence of shakedown subsequent to the onset of ratcheting. Hence, the design methods for thermal ratcheting and shakedown, proposed by the above mentioned and many recent works (e.g. Ponter and Karadeniz, 1985, Ueda et al., 1990, Majumdar, 1992, Maier et al., 1993, Plizzotto, 1993, Ng and Nadarajah, 1996 and many others), which are based on simplified elastic-perfectly plastic analysis, need analytical reevaluation and experimental validation.

In the ASME Boiler and Pressure Vessel Code (Subsection NB-3200 and NB-3600, ASME, 1998b), the requirement of primary plus secondary stress range limit of $3S_m$ is imposed to ensure shakedown. Data from material tests (Pilo et al., 1979) and elbow pipe tests (Acker et al., 1992) demonstrated that ratcheting may continue without shakedown even when the stress is limited to $3S_m$. Moreover, if the stress limit of $3S_m$ is exceeded, the ASME Code requires demonstration of shakedown through more detailed elastic-plastic analysis. But, experimental data indicate that, upon the onset of ratcheting, shakedown does not occur. In addition, widely used finite element programs, such as ANSYS and ABAQUS, cannot simulate ratcheting within reasonable accuracy. If shakedown does not occur after a few cycles, the conventional fatigue design methods which are based on strain- or displacement-controlled test data become progressively less reliable. Tagart (1972) and EPRI (1992) indicate that the fatigue life of piping components is reduced by the influence of ratcheting. Hence, in order to make piping component fatigue design methods more reliable, it is essential to understand ratcheting failure mechanisms more clearly and develop an improved finite element program to simulate ratcheting responses.

**Ratcheting and Shakedown at the Material level**

Benham (1960) performed a set of uniaxial ratcheting tests on pure annealed copper. Results from two of these tests are shown in Fig. 1a, where peak strain in each cycle is plotted as a function of number of cycles. In this figure, three distinct stages of ratcheting are clearly observed: (1) an initial transient stage, where the ratcheting rate gradually decreases with cycles, (2) a steady ratchet stage, which spans over most of the fatigue life of the material, and finally (3) a fracture stage, where ratcheting increases drastically. The initial transient stage is believe to be related to the cyclic hardening of annealed copper as demonstrated in Fig. 1b, where stress ranges from strain-controlled tests are plotted as a function of number of cycles. This cyclic hardening response and the transient ratcheting in the first stage probably gave the notion of shakedown; whereas, in reality, the material demonstrates steady ratcheting leading towards initiation of fracture and subsequent failure, rather than shakedown. The above mentioned three stages of ratcheting responses also have been demonstrated for mild steel and aluminum alloy by Benham and Ford (1961).

An interesting aspect of the ratcheting phenomenon is demonstrated by Pilo et al. (1979) for carbon steel. In a series of push-pull fatigue tests, they started with load-controlled push-pull cycles in the elastic range. A set of results from these tests is plotted in Fig. 2, where we see that the responses do not show any ratcheting or plastic strain during initial cycles. With progressive cycles carbon steel gradually softens which results in the onset of ratcheting and plastic strain simultaneously. This phenomenon is quite contrary to the conventional shakedown concept, which assumes shakedown of ratcheting to elastic or stable plastic strain cycles. Also note in Fig. 2a that the ratcheting responses have the three stages as discussed earlier. Similar ratcheting responses have been demonstrated by Wood and Bendler (1962) [see Fig. 16 in the reference], Moyar and Sinclair (1963) [see Fig. 3 in the reference], Benham (1965) [see Fig. 1 in the reference] and Hassan and Kyriakides (1994) [see Figs. 2a,b, and 4a in the reference] from biaxial material experiments.

**Ratcheting and Shakedown at the Structural Level**

Acker et al. (1992) conducted a series of quasi-static tests on elbow components subjected to in-plane cyclic bending with and without internal pressure. They demonstrated that when the maximum primary plus secondary stress range in elbow is below $3S_m$ no or very little ratcheting occurs with subsequent shakedown. However, as the primary plus secondary stress range reaches or exceeded $3S_m$, ratcheting in elbow shows no tendency of shakedown up to 1000 cycles. A set of tests on elbows through prescribing in-plane and out-of-plane dynamic excitation has been performed by Yahiaoui et al. (1996a, 1996b). Their test responses also demonstrate steady ratcheting without any tendency of shakedown up to 100 cycles (see Fig. 11 in the first reference and Fig. 7 in the second reference). Ueda et al. (1990) also demonstrated steady ratcheting of elbows subjected to alternate hot and cold cycles up to 100 cycles (see Fig. 4 in the reference).

**Conclusions and Discussion**

Material and piping component test data involving ratcheting deformation are studied in order to understand the shakedown phenomenon. The ASME Code requires the shakedown of ratcheting in order to ensure the safety of components. If shakedown occurs fatigue design of components can be performed using the conventional design method. The test data studied in this paper demonstrate no tendency of shakedown once the onset of ratcheting occurs. On the contrary, in most cases after an initial transient, ratcheting progresses at a steady rate. In the material tests, the steady rate of ratcheting leads toward initiation of fracture and subsequent failure. This observation raise the question of reliability of the components which are designed using conventional fatigue design methods, as reduction of fatigue life due to ratcheting has been reported in the literature (Tagart, 1979, EPRI, 1992). Hence, the assumption of the shakedown phenomenon as required by the ASME Code needs revisiting.

Most of the shakedown theorems proposed so far are based on simplified analysis and elastic-perfectly plastic material behavior. It have been shown by Hassan and Kyriakides (1994), Corona et al. (1996) and Bari and Hassan (1999) that constitutive models, like bilinear Prager, multilinear Mroz, and non-linear Chaboche and Dafalias-Popov models cannot simulate ratcheting responses within reasonable accuracy. Hence, the existing shakedown theorems need validation with respect to experimental ratcheting responses of piping components.

In addition, ratcheting is a complex function of multiaxial stresses (Hassan and Kyriakides, 1994). Uniaxial or simplified analysis models cannot capture the ratcheting responses of piping components. Hence, a reliable fatigue design method for piping components involving ratcheting needs to be developed through the following steps:

1. Conduct a systematic set of piping component tests up to failure. This set of data is required to clearly understand the ratcheting-fatigue failure mechanisms of piping components. Detailed strain and deformation data up to failure need to be recorded in these tests.
2. Conduct a set of material tests by prescribing strain and/or stress histories experienced by peak stress locations in the piping component tests. This set of data is needed to understand the initiation of ratcheting-fatigue crack in piping components and to develop improved constitutive models for simulation of ratcheting responses.
3. Incorporate the improved constitutive model into a finite element program to simulate ratcheting responses of piping components. The improved finite element program can be used to study the effects of geometry of components, type and level of loads, and to develop rational design methods for ratcheting in piping components.

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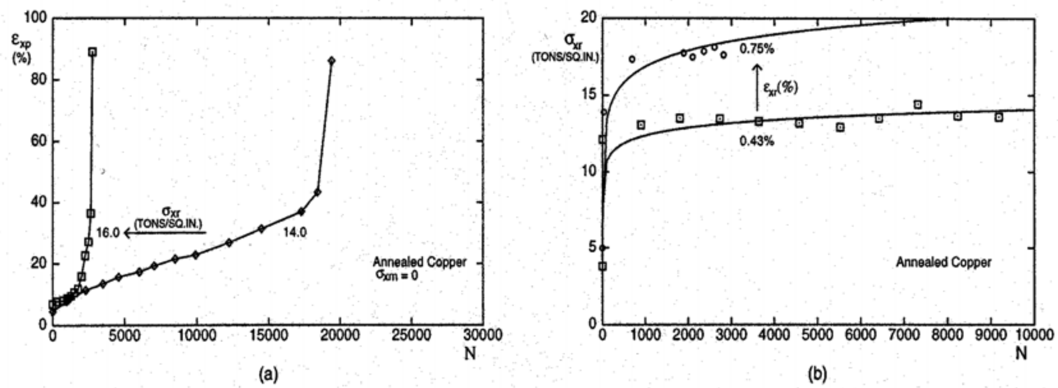


Fig. 1. (a) Uniaxial ratcheting of annealed copper subjected to stress cycles with zero mean stress, (b) cyclic hardening of annealed copper subjected to strain cycles (Benham, 1960).

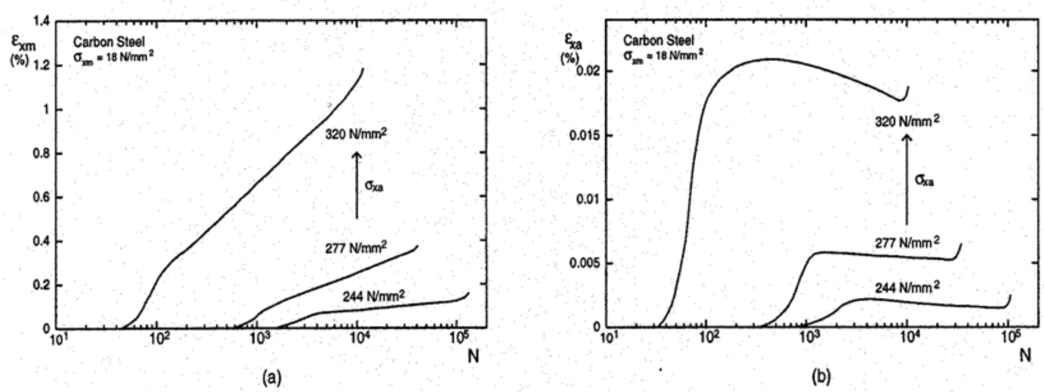


Fig. 2. (a) Uniaxial ratcheting of carbon steel subjected to stress cycles with mean stress, (b) cyclic softening and hardening of carbon steel subjected to stress cycles with mean stress (Pilo et al., 1979).