Special Section on Ratcheting

The design methods for pressure vessels and piping are based on the avoidance of potential modes of failure, such as collapse, excessive deformation, and cracking. Collapse and excessive deformation from a single load application are addressed by methods such as buckling analysis, primary stress analysis, and plastic limit analysis. For instance, limit load design underlies the evaluation methods for design conditions in most existing pressure vessel design codes.

When significant cyclic loading is applied, the evaluation of fatigue and ratcheting effects becomes necessary. Fatigue analysis is concerned with avoiding the initiation and propagation of cracks that could eventually cause a sudden fracture. Ratcheting is a failure mode typically associated with components that are subjected to pressure loading and simultaneously large cyclic thermal stresses. It is characterized by deformations or plastic strains that accumulate with increasing load cycles. Continued deformation can eventually render the component unserviceable and strain accumulation can accelerate fatigue cracking, which is not accounted for in the fatigue analysis.

Ratcheting can occur in metals, but also in nonmetallic materials. In order to avoid ratcheting, the cyclic loads must be kept within a specific limit that depends on the level of simultaneously applied mechanical loading (shakedown limit). By maintaining the stresses below the shakedown limit, some incremental plastic deformation may occur during the initial loading cycles, but the deformation in the subsequent cycles will be stable cycling, either in the elastic range (elastic shakedown) or involving alternating plasticity (plastic shakedown).

Typical simplified evaluation methods in the design codes are based on perfect (nonhardening) plasticity. Such methods and their extensions, such as direct methods of shakedown analysis, promise simple and efficient solutions and are still being developed. Due to the numerical methods that are now available, a full cyclic plastic simulation that could include work hardening is also becoming feasible. There are, however, some knowledge gaps in the application of hardening plasticity models to shakedown or ratchet analysis. For example, apparently equivalent descriptions of a plastic stress-strain curve by different plasticity models which give comparable results for static loading and even for steady cyclic response can have widely different ratcheting behavior. Depending on the plasticity model, the response may vary from guaranteed shakedown independent of loading to unexpected ratcheting under some stress states. Therefore, there is active research involving experimental studies of ratcheting and development of plasticity models to better describe the material response to various loading combinations. Simultaneously, efforts are underway to identify simple existing plasticity models that include hardening and are suitable for an engineering analysis of shakedown or ratcheting.

This special section on ratcheting has a total of 12 papers which represent a good mixture of theoretical, numerical, and experimental research in this area.

1 Theoretical Applications

The paper by Ahmadzadeh, Hamidinejad, and Varvani-Farahani studies ratcheting response of 1070 and 16MnR steel samples under uniaxial stress cycles using two advanced nonlinear kinematic hardening rules. The theoretical predictions are compared with each other. The choice of hardening rules in the assessment of ratcheting is further discussed based on the complexity of the hardening rule and number of constants/coefficients required to characterize ratcheting response.

The first paper by Hassan and Rahman on simulating the low-cycle fatigue and ratcheting responses of an elbow evaluates seven different constitutive models based on their simulation capabilities of the ratcheting response of a piping elbow specimen. The evaluated plasticity models range from a simple bilinear to advanced nonlinear models. The results of experiments conducted by the authors, which are presented in a separate paper under experimental work in this special section were used in developing a constitutive model that can simulate the ratcheting responses of piping components.

In the paper by Ure, Chen, and Tipping, the linear matching method (LMM) is discussed, a direct numerical method for determining shakedown and ratchet limits that has seen significant development recently. Based on classical theory, the method can provide upper and lower bounds to the shakedown limit. The results of LMM analysis for limit loads and shakedown limits are compared with experimental results available from the literature. The limit load and shakedown limits were obtained for pipe intersections and nozzle-sphere intersections.

The paper by Adibi-Asl and Reinhardt derives the interaction diagrams based on perfect plasticity for a beam subjected to primary membrane and bending with secondary bending loads. Various cross sections including rectangular, solid circular, and thin-walled pipe are investigated. The solutions are based on non-cyclic method previously proposed by the authors; this method is extension of static shakedown theorem (Melan's theorem) to predict the entire ratchet boundary (both elastic and plastic).

2 Numerical Methods

The paper by Weichert, Hachemi, and Simon focuses on recent progress in numerical shakedown and limit analysis based on Melan's lower bound shakedown theorem. The theoretical foundations of the optimization based approach are discussed first, followed by details of the numerical scheme proposed by the authors. Numerous examples in area of related to pressure vessel technology are presented.

The contribution by Kalnins, Rudolph, and Willuweit discusses the use of Chaboche's nonlinear kinematic hardening model for ratcheting simulations. The paper describes methods to obtain a representation of the stress-strain needed for such simulations. Two different methods were selected for model calibration, and it is shown that both can determine the parameters for stainless steels. The use of the Chaboche parameters for cases when

ratcheting is caused by cyclic temperature fields is selected as an application of the model.

The paper by Hafiz, Younan, and Abdalla proposes a simplified assessment procedure, for the API 579 standard, for elastic shake-down and limit load analyses. The proposed procedure is applied to a pipe-branch connection with local wall thinning subjected to a spectrum of steady internal pressures and cyclic bending moments. The results are then compared with the existing elastic and elastic-plastic assessment procedures in the API 579 standard.

3 Experimental Work

The two papers by Wang, Sham, and Jetter present experimental data for thermal ratcheting test of a two-bar model made of Alloy 617 at very high temperatures. The bars were heated and cooled out of phase to generate thermally induced loading superimposed on a constant mean stress. Scoping test results at slow heating and cooling rates are presented for different mean stresses and thermal histories, followed by actual ratcheting tests. The testing conditions of the ratchet tests were designed to be closely aligned to the development of design rules for strain limits at very high temperatures for Alloy 617.

The contribution by Hassan, Rahman, and Bari investigates low-cycle fatigue and ratcheting responses of elbows through experimental study. A set of fatigue and ratcheting responses for stainless steel 304L 90 deg long-radius elbow specimens is obtained by conducting displacement controlled and force-controlled cyclic experiments. The results of this work are used in developing a constitutive model that can simulate ratcheting responses of piping components which is presented in a companion paper (under theoretical applications) in this special section.

The paper by Ravikiran, Dubey, Agrawal, Reddy, Singh, and Vaze describes experimental and numerical studies concerning the inelastic response of pressurized piping system under seismic loading. Shake table tests were carried out on a three-dimensional stainless steel piping system under internal pressure and seismic

load. The amplitude of base excitation was increased until failure of the piping system was observed. Failure was by fatigue-ratcheting. The tested piping system was analyzed using iterative response spectrum method for various levels of excitation. The comparison of numerical and experimental results is given in the paper.

The paper presented by Bouzid and Benabdallah investigates the effect of thermal cycles and a few considerations that can be made to improve the characterization procedure for better prediction of the long-term performance of Teflon-based gaskets at high temperature. The gaskets fail by a ratchet-like incremental mechanism over several loading cycles. A special test procedure was developed to characterize and qualify this type of gaskets.

Acknowledgment

The guest editors would like to thank all the authors for their contributions to this special section and all the reviewers for their valuable evaluations and constructive suggestions. Special thanks to Dr. Young Kwon, Editor-in-Chief of ASME JPVT, for supporting this project throughout.

We hope that this special section will be useful and informative for our readers and provides a useful update on the latest experimental and theoretical results in the description of shakedown and ratcheting.

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