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A two-rod testing approach for understanding ratcheting in structures



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ABSTRACT

In a national project, with the aim to develop a robust method for structural verification of pressure equipment subjected to ratcheting, a two-rod test approach is developed. Two testing machines, with one specimen in each, are controlled in such way that a constant primary load and a cyclic secondary load are applied on the specimens. The ferritic steel P265 and the austenitic steel 316L are tested for a number of load combinations. Test results show that ratcheting is produced in all tests. As expected, the amount of ratcheting increases with the load level. At the start of a two-rod test, structural ratcheting dominates over material ratcheting. Depending on the load level and combination of primary load and cyclic secondary load, material ratcheting might eventually become more important.

Based on results from tensile testing and fully-reversed strain controlled cycling, five different constitutive models are calibrated. The possibility to simulate the response of the conducted experiments with the different models is investigated. The most advanced model investigated, i.e. the nonlinear kinematic Chaboche model, does not necessarily give the best predictions. Up to a strain level of 5%, i.e. the criterion in ASME NB-3228.4, the bi-linear model best predicts the experiments.

Recommendations for how ratcheting in structures subjected to cyclic plastic deformation can be predicted by numerical simulation are given.

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1. Introduction

Ratcheting is defined as progressive incremental plastic deformation resulting from cyclic loading. A consequence of ratcheting can be wall thinning, excessive deformation or, if proceeding too long, failure of the component. In order to avoid such failures, design codes for mechanical structures specify criteria that have to be fulfilled. The ASME Boiler & Pressure Vessel Code [1] is an example of a design code that addresses the ratcheting mechanism.

Ratcheting can be divided in material ratcheting and structural ratcheting [2]. A steel specimen subjected to uniaxial stress cycling with a nonzero mean stress can show material ratcheting if plastic deformation occurs in both tension and compression. Material ratcheting is a phenomenon that is related to the characteristics of the material and its response at a microstructural level. A well-known case where structural ratcheting can be produced is the Bree test where a pressurized cylinder is subjected to a cyclic temperature gradient through the wall thickness [3]. In this test, stresses caused by the internal pressure are constant and load

controlled in contrast to the thermal stresses that are cyclic and deformation controlled. Starting from the stress state caused by the internal pressure and assuming that the load level is such that structural ratcheting is facilitated, application of the temperature gradient through the wall thickness will cause the stresses to increase in the region where temperature is lowered and decrease in the region where temperature is increased. During the first half cycle of a Bree test, one part of the wall thickness undergoes plastic deformation while the remaining part acts as a dolly and stays elastic. During the consecutive half cycle, plastic deformation occurs at the opposite side of the wall thickness. Now as the thermal cycling continues, ratcheting will occur in the cylinder resulting in thinning of the wall thickness and an increase of the diameter. The driving force causing the change in geometry in the Bree test is the internal pressure.

A simple structure is preferable as a starting point when investigating ratcheting in mechanical components. For simplicity and clarity, Miller begins by examining a three-bar assembly in Ref. [4]. Three parallel elastic-plastic bars are loaded with a constant force and a cyclic temperature load. Materials with and without strain-hardening are studied. Subsequently, a pressurized pipe subjected to cyclic thermal loading is investigated. Both linear and parabolic temperature distributions are assumed. Finally,

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correlation between the three-bar assembly and the pressure vessel is discussed. Tension bending ratcheting tests of 304 stainless steel are performed at two temperatures [5]. Uniaxial specimens are loaded by a constant axial force and a superimposed cyclic deformation controlled bending. For the load combinations investigated, shakedown is demonstrated in the 288 °C tests but not the room temperature tests. It is suggested that reported results may be used to develop improved ratcheting and shakedown rules permitting a relaxation of the traditional ratcheting rules in the ASME Boiler & Pressure Vessel Code [5]. Garud [6] performs a review and an assessment of ratcheting considerations for design and analysis. A two-bar assembly is used to illustrate the key characteristics of ratcheting. The effect of strain-hardening, type of ratcheting, i.e. material or structural, and stress state is discussed. According to Garud [6], ratcheting is mostly a result of some non-symmetry either in the loading or the material (stress–strain) character.

Ratcheting in pressurized components has been extensively investigated. Common for these investigations is often that a constant internal pressure is applied in combination with a cyclic deformation controlled load. In Ref. [7], a straight pipe subjected to a constant internal pressure and a deformation controlled bending is numerically investigated with different constitutive models. For the cases studied, suggested model in Ref. [7] showed significant improvements compared to available models in commercial FE codes. In Ref. [8], ratcheting in a pressurized pipe subjected to cyclic axial displacement is investigated both experimentally and numerically. Based on results from this study, it is recommended the Besseling material model [9] is used for robust structural verification of pressurized components subjected to ratcheting. In contrary to [7,8], the cyclic load in Ref. [10] is load controlled. In this study, a quasi-three point bending apparatus is used to investigate ratcheting in a pressurized straight pipe subjected to a cyclic bending load. Despite the difference in character of the cyclic loads, progressive deformation occurs in the hoop direction in all three investigations [7,8,10].

In this paper, ratcheting in the ferritic steel P265 and the austenitic steel 316L is investigated both experimentally and numerically. The experimental part includes material characterisation and two-rod testing. The numerical part includes an evaluation of the possibility to predict the two-rod experimental results by use of different constitutive models. The possibility to apply the two-rod concept on multiaxial stress states is also investigated as well as its application with respect to the ASME Boiler & Pressure Vessel Code [1].

2. Two-rod test approach

The structure consists of two parallel rods that are subjected to a constant primary load F corresponding to an average primary stress σ_{prim} in combination with a cyclic secondary load applied as a cyclic elongation difference between the two rods, see Fig. 1. The elongation difference corresponds to an elastically determined stress range given as

$$\Delta\sigma_{sec} = E \cdot \frac{\Delta\delta}{l_0}$$

where E is Young's modulus, $\Delta\delta$ is the elongation difference between the two rods and l_0 is the measuring length of the rods, i.e. the distance between extensometer knife edges.

At the start of a two-rod test, a constant primary load is applied resulting in tension in both rods. Subsequent application of an elongation difference between the rods will, if large enough, result in plastic deformation in the most pulled rod while the least pulled

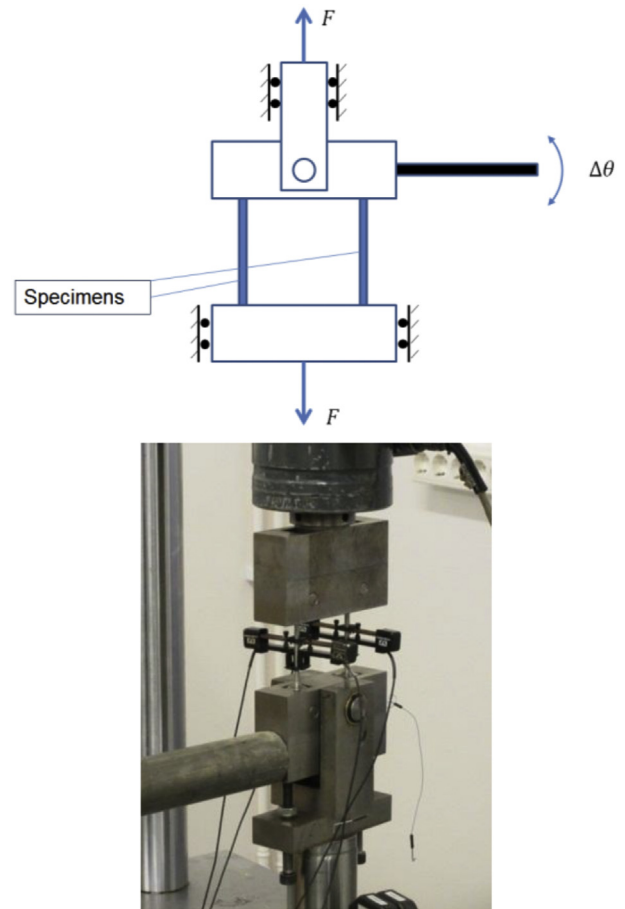


Fig. 1. Schematic figure of a two-rod test. Joints where the specimens are attached to the blocks are not shown (above). First prototype of two-rod test rig (below).

rod stays elastic. In this sequence of the test, the least pulled rod acts as a dolly. In the following half cycle, the response of the two rods will switch. As the secondary cycling continues, the averaged strain of the rods will increase caused by structural ratcheting. If the least pulled rod starts to deform plastically in compression, material ratcheting might occur. The ratcheting might eventually cease if the material shows cyclic hardening.

In the two-rod experimental setup, two testing machines are used in parallel with one specimen in each, see Fig. 2. The difference between signals from the two extensometer pairs and the sum of the forces in the two load cells are used to control of the testing machines. Standard specimens are used.

3. Material characterisation

Tensile testing and fully-reversed strain controlled cycling are conducted for characterisation of the two materials P265 and 316L. The specimen strain measurements are done by use of two 12.5 mm extensometers. All tests are conducted at room temperature. In summary, $R_{p,0.2}$ equals 298 and 293 MPa for P265 and 316L, respectively. Plastic hardening and cyclic hardening is more pronounced for 316L than for P265. Additional information about the material characterisation is given in Refs. [11] and [12].

4. Two-rod test load combinations

The two-rod test load combinations investigated for P265 and 316L are shown in Tables 1 and 2, respectively. Stresses are given as

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