SMiRT-12 / K. Kussmaul (Editor)

L08/2

RATCHETTING IN PRESSURISED PIPES

I.D. Charles[1], S.J. Harvey[2] and R.J. Rider[2]

[1]D.C. White and Partners, Ancell Business Park, Fleet, Hampshire GU13 8UY, UK
[2]School of Engineering, Coventry University, Priory Street, Coventry CV1 5FB, UK

ABSTRACT

The plastic deformation of thin-walled cylinders has been experimentally examined for the loading conditions of ±1% axial strain with hoop stresses of approximately 0, 1/4, 1/2 and 3/4 of the initial uniaxial yield stress.

Two materials similar to those used in the pipework of PWR nuclear plant in the U.K. have been tested, namely 304S11 stainless steel and En6 low-carbon steel. The results of the tests were to be compared with the allowable stresses and deformations specified in the ASME Boiler and Pressure Vessel Code, Section III. The code specifies that a prescribed combination of primary stresses must not exceed S_m, where S_m is a stress intensity value defined for each material.

The results indicate that the limit of $1.5S_m$ is excessively low for both materials and that in particular, the stainless steel could tolerate $5S_m$. Although the En6 steel is more prone to ratchetting than the stainless, the results suggest that it too could tolerate a higher primary stress that the code allows. Both materials are shown to satisfy the proposed ASME ratchet strain limit of 5% hoop strain after 10 cycles of ±1% axial strain range, for any value of internal pressure used.

1. INTRODUCTION

In the nuclear power industry, the safety and integrity of pressurised vessels and large piping runs is of particular concern, especially when they are subjected to high-strain, low-cycle fatigue conditions such as may be induced by seismic disturbances. It has been suggested [1], that the design code [2] is over-conservative when considering seismic and other cyclic loads. The conservatism in the design rules can lead to excessive piping support to accommodate infrequent dynamic loads and result in over-restraint which can lead to higher thermal stresses. The current design codes for assessing piping failure are based on static collapse rather than incremental collapse or low-cycle fatigue mechanisms. These procedures will no doubt continue until a satisfactory model of strain accumulation in incremental collapse or ratchetting is established. The purpose of this research was to examine the ratchetting strains in piping subjected to cyclic plastic push-pull with a steady internal pressure and to compare the results obtained with the code guidelines.

2. APPLICATION OF THE ASME III CODES TO BOILERS AND PRESSURE VESSELS

Of concern here are the component design rules and in particular how seismic loading should be regarded within the rules. The rules are based on static loading and are intended to protect against component failure by rupture, plastic collapse or fatigue. Dynamic loads are generally treated as quasi-static and the usual practice is to calculate stresses by combining static and dynamic loads and comparing these to allowable stresses based on static loading.

For the purposes of calculation, the code recognises three categories of stress :-

2.1 Primary Stress - Non self-limiting stress caused by the applied external loads, and subdivided as :-

2.1.1 General Primary Membrane Stress
2.1.2 Local Primary Membrane Stress
2.1.3 Primary Bending Stress

2.2 Secondary Stress - Self-limiting, displacement controlled stress, e.g. thermal stress. Local yielding and minor distortions can be tolerated.

2.3 Peak Stress - The highest stress in a region. May be of concern at a notch or defect as a source of failure by fracture or fatigue.

Stresses due to both pressure and seismic loads are classified within the code as primary stresses. Experimental evidence however shows that the failure mode of pipework subjected to reversed dynamic loads is by ratchetting and fatigue. It could therefore be argued that seismically induced stresses should be treated as secondary (displacement controlled) rather than primary (load controlled).

3. MATERIALS AND TEST PROCEDURES

Two materials similar to those commonly used in nuclear plant pipework were chosen, namely an austenitic stainless steel 304S11 and a low-carbon steel, En6. The stainless steel was used in the as supplied condition, i.e. fully softened and de-scaled. The En6 steel was normalised and shot-blasted prior to machining. Thin-walled tubular push-pull specimens were manufactured from each material with a nominal gauge length of 40 mm, an outer diameter of 22 mm and bore of 20 mm.

The specimens were tested under strain-controlled cyclic push pull conditions of ±1% axial strain at a rate of 0.1%/min, using a test rig fully described elsewhere [3]. Additionally internal pressures were applied hydraulically, allowing the cyclic loading to be combined with static tensile hoop stresses of nominally 0, 1/4, 1/2 and 3/4 of the uniaxial yield stress. Tests were conducted both with the axial strain initially compressive and with the axial strain initially tensile. Tests were limited to 15 cycles of cyclic strain in order to avoid excessive amounts of buckling of the specimen gauge length.

Axial strains were measured using a matched pair of diametrically opposed LVDT's with an overall system resolution of 5 $\mu\varepsilon$. Hoop strain was measured with a radially free-floating LVTD with an overall system resolution of 2 $\mu\varepsilon$. Axial loads were measured with a Carl Schenk U2 load cell and hydraulic pressure with a Druck PDCR 100 pressure transducer.

All transducer outputs were digitally sampled using a 12-bit A-D converter operating via a sequencing card. This enabled transducer outputs to be sampled simultaneously every 200 ms. The push-pull stroke was controlled by reversing a stepper motor drive when the axial strain reached the ±1% limit.

4. EXPERIMENTAL RESULTS

Typical results for the stainless steel 304S11 with initially tensile axial strain are shown in figs. 1a to 1c. Fig. 1a (hoop stress ≈ 1/2 yield) shows that after the first 1/4 cycle, the material rapidly cyclically hardens to a stable hysteresis loop. (Within 2 cycles) With no internal pressure, the hysteresis loop would be symmetrical, with peak stress of about ±510 N/mm^2. With non-zero hoop stresses, the asymmetry in the hysteresis loop merely reflects the asymmetry (in a plasticity sense) of the loading conditions. The resulting hoop ratchetting behaviour under this load combination is shown in fig. 1b. This shows that about 40% of the hoop strain accumulation occurs during the first full cycle. It is also worth noting that after the first 1/4 cycle, the rate of hoop deformation within subsequent 1/2 cycles is neither qualitatively or qualitatively predicted by classical plasticity hardening theories. The overall rate of hoop strain accumulation per cycle for each of the internal pressures used is shown in fig. 1c. From this is may be noted that even with the highest value of hoop stress, the accumulated hoop strain after 10 cycles is only 1.5%.

Typical results for the low-carbon steel En6 with initially compressive axial strains are shown in figs. 2a to 2c. Fig. 2a (hoop stress ≈ 3/4 yield) shows that this material again cyclically hardens but at a lower rate than the 304S11 and does not reach a stable hysteresis loop until the fourth cycle. Peak stress are again asymmetric due to the loading conditions. Fig. 2b shows that the hoop ratchet process is much faster than for 304S11 but with a qualitatively similar rate of hoop deformation. The high rate of hoop strain accumulation is reflected in fig. 2c and with this material it can be seen that after 10 cycles with a hoop stress ≈ 3/4 yield, almost 5% of hoop strain has been accumulated.

5. APPLICATION OF ASME III COMPONENT DESIGN RULES

ASME III requires that the consideration of seismic loads must fulfil two criteria. Firstly, the peak seismic stress must be regarded as a primary stress and in a specified combination of other primary stresses must be $\leq 1.5S_m$, where S_m is a prescribed stress intensity. This is intended to protect against a 'static' type failure. Secondly, in order to protect against failure by fatigue and incremental collapse, the total plastic strain accumulation after 10 cycles must not exceed a prescribed figure. For the loading conditions described here, this equates to a limit of 5% accumulated plastic hoop strain.

For the two materials used, ASME defines S_m as 115 N/mm^2 for 304S11 and as 138 N/mm^2 for En6, thus producing $1.5S_m$ limits of 173 N/mm^2 and 207 N/mm^2 respectively.

Comparison of the ASME limits with the results presented shows that the 304S11 is comfortably exceeding both criteria. e.g. with a peak cyclic stress of about 550 N/mm^2 and a hoop stress of 97 N/mm^2, giving a stress intensity of about 600 N/mm^2 ($5.2S_m$), the specimens do not rupture or collapse. Additionally, accumulated hoop strains of approximately 1.5% after 10 cycles are well below the 5% ratchet limit. The En6 material also exceeds the criteria but by a narrower margin. At a hoop stress of 127 N/mm^2 the loading is equivalent to $3.5S_m$ and with a compressive pre-stress, 4.5% plastic hoop strain is accumulated after 10 cycles but without imminent danger of failure.

6. CONCLUSIONS

The results suggest that for the experimental conditions used, the ASME III limit of $1.5S_m$ is over-conservative for the 304S11 stainless steel which was tested at levels exceeding $5S_m$. The code is also conservative for the low-carbon steel, En6 but to a lesser degree, with stress intensity levels in excess of $3.5S_m$ not producing failure. It might therefore be suggested that different levels be adopted for different materials.

Continued application of the test conditions would ultimately produce failure by fatigue but for both materials, well beyond the ASME III limits with the tests giving maximum hoop strain accumulations after ten cycles of about 1.5% and 4.5% for the 304S11 and En6 materials respectively.

7. REFERENCES

1. Rangarth,S. 1990. "Piping and Fitting Dynamic Reliability Program Vol. 1-5". GE Nuclear Energy EPRI Contract RP1543 - 15.

2. ASME Boiler and Pressure Vessel Code, Section III. 1989

3. Charles,I.D. 1992. Ratchetting Strains in Pressurised Pipes. Ph.D. Thesis. Coventry Polytechnic CNAA.

Fig.1. Stainless Steel 304S111 - Tensile Axial Pre-stress

Nominal Hoop Stress @ 1/2 Yield ≈ 100 N/mm^2

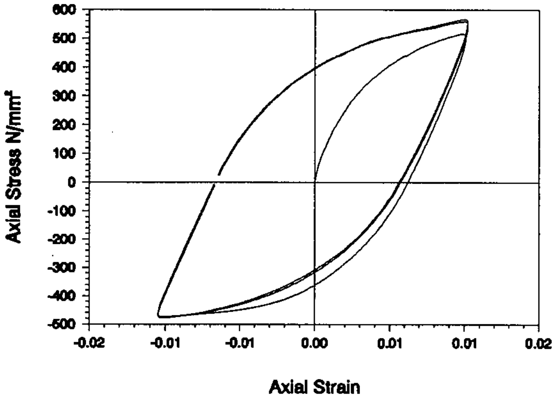

Fig 1a. Cyclic Hysteresis Loop - 1/2 Yield

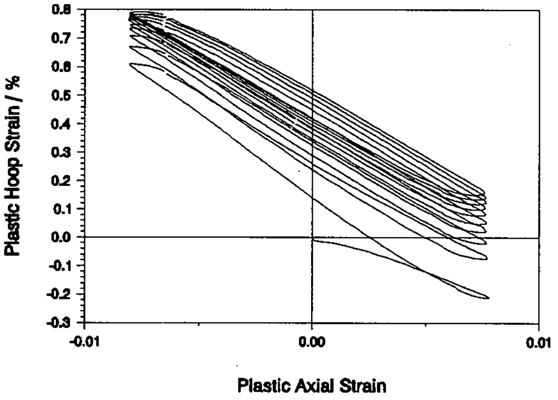

Fig 1b. Hoop Strain Ratchetting - 1/2 Yield

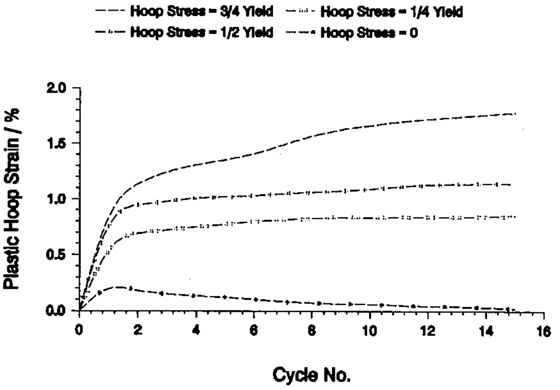

Fig 1c. Plastic Hoop Strain Accumulation

Fig.2. En6 Low Carbon Steel - Compressive Axial Pre-stress

Nominal Hoop Stress @ 1/2 Yield ≈ 130 N/mm^2

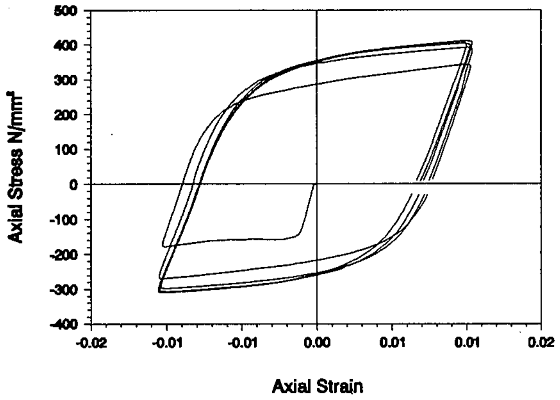

Fig 2a. Cyclic Hysteresis Loop - 1/2 Yield

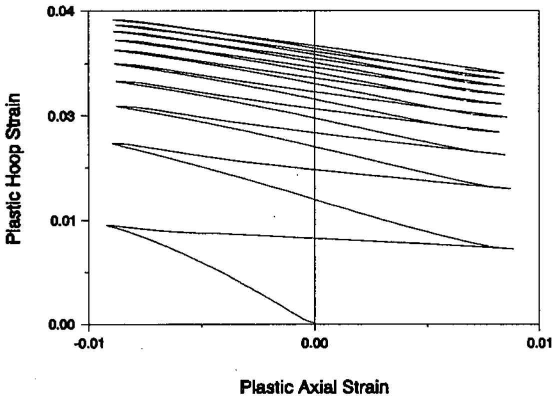

Fig 2b. Hoop Strain Ratchetting - 1/2 Yield

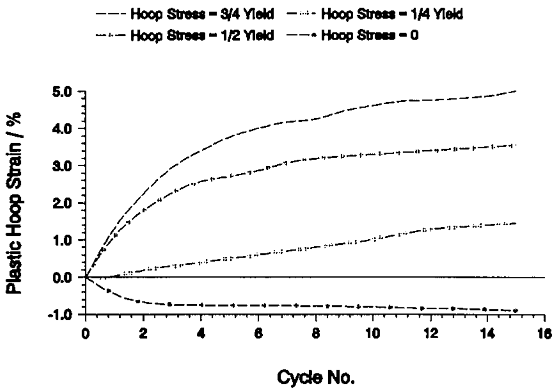

Fig 2c. Plastic Hoop Strain Accumulation