Evaluation of cyclic plasticity in high pressure reactors with stress concentrators

Grzegorz Widłak[1] **and Andrzej P. Zieliński**[2]

[1]*Institute of Machine Design, Cracow University of Technology*
al. Jana Pawła II 37, 31-864 Cracow, Poland
e-mail: widlak@mech.pk.edu.pl

[2]*Institute of Machine Design, Cracow University of Technology*
al. Jana Pawła II 37, 31-864 Cracow, Poland
e-mail: apz@mech.pk.edu.pl

Abstract

An evaluation of localized cyclic plasticity occurring in the regions of stress concentrators in high-pressure reactors is presented in this article. The investigation of material model which is intended to represent cyclic plasticity (the Armstrong-Frederick model) proved that the ratchetting rate in the reactor structure is significant at the initial process stage and further is kept constant, which eventually leads to the failure due to incremental plastic collapse. The linear constitutive model (Prager hardening rule) is not intended to define cyclic plasticity. A plastic modulus, which is the same for loading and unloading (no effect of mean stress) results in the stress cycles which form a closed hysteresis loop.

Keywords: cyclic loadings, plasticity, ratchetting, high- pressure vessels

1. Introduction

High-pressure, thick-walled cylindrical vessels, which are used in the petrochemical and other process industry are usually subject to cyclic mechanical and thermal loads. Such vessels very often have small radial holes in their walls, which are necessary for media transmission and attachment of instrumentation. These holes are strong stress concentration sources and in their vicinity plastic effects can often occur. Therefore, it is essential to design the vessels against cyclic plasticity failure mechanisms, which can result in development of cracks dangerous for the whole structure. The cracks of this kind were observed in one of polyethylene reactors in the petroleum refinery in Poland (Ref. [1,2]). They appeared near a small hole for discharging the reactor from the final product (Fig.1). The purpose of the present work is, therefore, to examine closely and comprehensively this important industrial problem with respect to local plasticity effects during cyclic operating of the reactor.

2. Computational model

In the present study a mechanism of development of reverse plastification is illustrated. Two different kinematic hardening rules are presented in the context of ratchetting evaluation. The first is Prager linear hardening rule. The second is nonlinear hardening model proposed by Armstrong and Frederick.

2.1. Material models

The rate-independent plasticity model used in this study is assumed to exhibit kinematic hardening with the Huber – von Mises yield condition. Therefore, the equivalent stress can be defined as:

$$\sigma_e = \left(\frac{3}{2}(\mathbf{S}-\mathbf{a}):(\mathbf{S}-\mathbf{a})\right)^{1/2} \tag{1}$$

where $\mathbf{S}$ is the deviatoric stress tensor and $\mathbf{a}$ denotes the back stress deviator, representing current center of the yield surface. The yield function:

$$f = \sigma_e - Y_0 \tag{2}$$

gives yield condition $f = 0$, which must hold throughout the plastic response. The size of the yield surface is denoted by Y_o, which remains constant in kinematic hardening models. There are many formulations of coupled kinematic models (Ref.[3]). Prager proposed the simplest possible form of evolution of the yield surface during plastic straining by linear translation in the stress space:

$$\dot{\mathbf{a}} = \frac{2}{3} C \dot{\boldsymbol{\varepsilon}}^{\mathbf{pl}} \tag{3}$$

This model is very popular in engineering computations, because it needs only one plastic parameter *C*. Despite the fact that this model could reasonably represent the shape of some monotonic stress-strain curves, it fails to produce ratchetting in uniaxial tests. Moreover, rapid prediction of shakedown in the initial cycles of multiaxial loading does not match experimental results.

The most well known nonlinear kinematic hardening model was proposed by Armstrong and Frederick. They enriched the Prager rule (Eqn. (3)) by a term proportional to the current back stresses. As the back stress develops, the additional term is activated, which slows down the rate of the yield surface evolution:

$$\dot{\mathbf{a}} = \frac{2}{3} C \dot{\boldsymbol{\varepsilon}}^{\mathbf{pl}} - \gamma \mathbf{a} \dot{\varepsilon}_{eq}^{pl} \tag{4}$$

The expression '$-\gamma \mathbf{a} \dot{\varepsilon}_{eq}^{pl}$' is considered as a recall term, which introduced a fading memory effect of the strain path .

2.2. FE model

In high-pressure reactors, the pressure load and thermal gradients usually have cyclic character, therefore it is essential to develop a FE model, which is appropriate for accurate and effective cyclic plasticity simulations. Estimation and investigation of the robust integration algorithm of constitutive equations, which is herein used, can be found in Ref.[4]. A commercial software ANSYS is utilized to obtain FE model.

It has been assumed that the investigated reactor has the form of thick-walled cylinder with internal radius a=150 mm, external radius defined by ratio a/b =0,7 and radial hole which diameter ratio is d/a = 0,05.

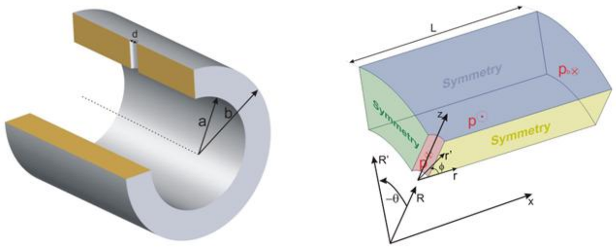

Figure 1: Geometry and boundary conditions of investigated reactor

3. Ratchetting evaluation

When reactor loads exceed elastic shakedown limit, a phenomenon of cyclic plasticity occurs, which is a cause of fatigue failure in very-low-cycle and low-cycle regimes. In addition to alternating plasticity, a ratchetting response is often present, accounting for acceleration of fatigue damage or acting as a failure mechanism itself. In the following, stress-strain hysteresis curves are presented for the maximum effort point in the radial hole vicinity.

3.1. Linear model

For the Prager hardening rule, there are no significant changes in the plastic strain history. After initial, relatively large plastification, a reverse plasticity is observed due to strong compressive effects after unloading. A slight difference between magnitudes of plastic strain increments during loading and unloading is noticeable only for the first three cycles. Further, an integral of every component of plastic strain tensor is practically equal to zero over each individual cycle. The constitutive model is not intended to define cyclic plasticity and has a plastic modulus, which is the same for loading and unloading (no effect of mean stress). Therefore, in the stress cycles a closed hysteresis loop is generated (Fig. 2).

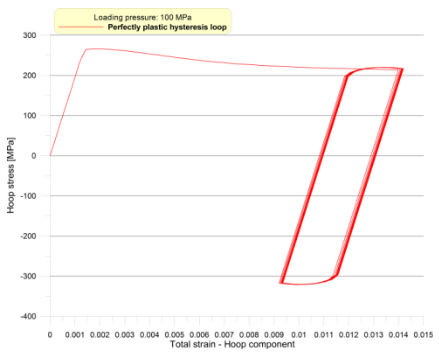

Figure 2: Hysteresis loop – Prager model

3.2. Nonlinear model

The nonlinear constitutive models incorporate a term proportional to the current back stresses. The main idea of this term is observed for the cyclic plasticity with the large mean stress-strain state, which is observed in the reactor structure. A change in shape of positive (decreased plastic modulus) and reverse (increased plastic modulus) loading curves is observed. Therefore, for almost constant stress-strain variations, loops do not close, resulting in ratchetting. Finally, after some redistribution effects, a significant slowdown of the ratchetting rate is observed, but small, decreasing translations of the hysteresis curve can be noticed in each cycle (Fig. 3).

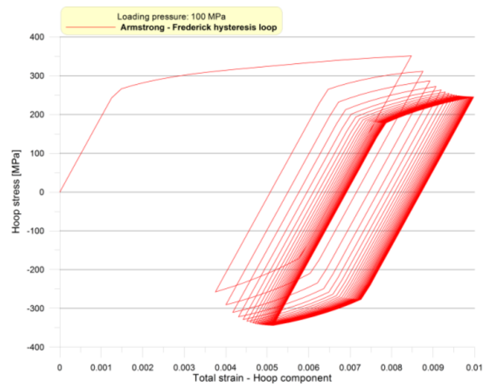

Figure 3: Hysteresis loop – Armstrong and Frederick model

4. Conclusions

Investigation of the inadaptation range, showed that the linear kinematic hardening excludes ratchetting. More appropriate definitions of material (the Armstrong-Frederick model) proved that the ratchetting rate can be significant

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