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Ratcheting behaviour of elasto-plastic thin-walled pipes under internal pressure and subjected to cyclic axial loading

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ABSTRACT

The present paper is concerned with the analysis of the ratcheting behaviour of elasto-plastic thin-walled pipes under internal pressure and subjected to cyclic axial loading. Understanding the behaviour of this kind of structure at different load levels is of critical importance in a range of engineering applications such as in the design of structural components of power and chemical reactors. Depending on the kinematic hardening, the pipe may exhibit a ratcheting behaviour in the circumferential direction, which leads to a progressive accumulation of deformation. Many different constitutive theories have been proposed to model the kinematic hardening under such kind of loading history. The present paper presents a simple local criterion to indicate whether or not the pipe may exhibit a progressive accumulation of deformation. Such criterion is independent of the choice of the evolution law adopted for the backstress tensor. As an example, a semi-analytic approach using a mixed nonlinear kinematic/isotropic hardening model is proposed to be used in a preliminary analysis of this kind of structure.

1. Introduction

When a metallic component is subjected to cycles of mechanical loading beyond the elastic limit many important phenomena can occur, what may lead to structural failure. Different structural situations exist in which this combination of sustained or primary loading and secondary cyclic loading can lead to incremental collapse or what is known as ratcheting. For instance, pressurised metallic tubes under reversed bending [1] or pressurised metallic tubes subjected to cyclic push pull [2]. These structures under such load combinations are known to exhibit continued strain growth in the hoop direction.

Understanding the behaviour of this kind of structure at different load levels is of critical importance in a range of engineering applications such as in the design of structural components of power and chemical reactors (primary heat transport system of nuclear power plants, for instance). The reliability of structural integrity prediction depends strongly on the physical adequacy of the elasto-plastic constitutive equations considered in the analysis. Many papers concerned with ratcheting failure mechanisms or with constitutive models for ratcheting have been performed in the last years. Since the classical works of Chaboche (see [3], for instance), most works were concerned with an adequate modelling of the kinematic hardening to improve the description of ratcheting effects and to include a better modelling of multiaxial behavior [4–7]. In [4], a complete model was developed, including isotropic hardening, to describe the ratcheting behaviour of 316L stainless steel at room temperature. In this study, one particular kinematic hardening rule was selected aiming at describing both the shape of the normal cyclic stress–strain relations and the ratcheting results. The main concern, as discussed in [5], was to propose rules that induce much less accumulation of uniaxial and multiaxial ratchetting strains than the Armstrong and Frederick rule. In [5], kinematic hardening rules formulated in a hardening/dynamic recovery format were examined for simulating racheting behaviour. These rules, characterized by decomposition of the kinematic hardening variable into components, are based on the assumption that each component has a critical state for its dynamic recovery to be fully activated. In the paper by Abdel Karim and Ohno [6], an alternative kinematic hardening model was proposed for simulating the steady-state in ratcheting within the framework of the strain hardening and dynamic recovery format. The model was formulated to have two kinds of dynamic recovery terms, which operate at all times and only in a critical state, respectively. The model is able of representing appropriately the steady-state in ratcheting under multiaxial and uniaxial cyclic loading. In [7], seven cyclic plasticity models for structural ratcheting response simulations were analysed: bilinear (Prager), multilinear (Besseling), Chaboche, Ohno–Wang, Abdel Karim–Ohno, modified Chaboche (Bari and Hassan) and modified Ohno–Wang (Chen and Jiao). Apparently, none of the models evaluated perform satisfactorily in simulating the straight pipe diameter change and circumferential strain ratcheting responses.

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In particular, many experimental and numerical studies on ratcheting induced by reversed bending in straight pipes and elbows have been performed in the last years [1,8–10], and a detailed review can be found in [1,10]. In [1], ratcheting studies were carried out on Type 304LN stainless steel straight pipes and elbows subjected to steady internal pressure and cyclic bending load. Ratcheting behaviour of straight pipes and elbows were compared and it was generally inferred that ratcheting was more pronounced in straight pipes than in elbows. Shariati et al. [8] investigated the softening and ratcheting behaviours of SS316L cantilevered cylindrical shells under cyclic bending load. Accumulation of the plastic strain or ratcheting phenomenon occurred under force-control loading with nonzero mean force. It was verified that an increase of the mean force induces an increase in the accumulation of the plastic deformation and its rate. Plastic mechanism analyses of circular tubular members under cyclic loading were performed in [9]. This paper provides new methods of analyses for circular hollow sections subjected to a constant amplitude cyclic pure bending and a large axial compression–tension cycle. The local buckling analysis was performed using a rigid plastic mechanism analysis.

Although ratcheting based criteria for integrity assessment of pressurized piping under severe loading can be found in codes [11], so far most constitutive models are unable to describe the complex nonlinear cyclic behaviour observed in this kind of problem. Besides, the analysis of the stress and strain fields usually requires the use of complex finite element codes, what can be a shortcoming for the effective use of these theories by designers.

The present paper is concerned with the analysis of the coupled effect of kinematic and isotropic hardening on the multiaxial ratcheting behaviour of elasto-plastic thin-walled straight pipes under internal pressure and subjected to cyclic axial loading. An easily employable framework to be used in the analysis of structures of this type with complex material behaviour, as elasto-plasticity with both isotropic and kinematic hardening, is presented. A simple and efficient algorithm for approximating the solution is described.

Simulations of AISI 316L steel and AU4G aluminium alloy pressure vessels at room temperature subjected to multiaxial loadings are presented and analysed. It is shown that cyclic behaviour is strongly dependent on the kinematic hardening, but also on the isotropic hardening. The main result of the paper is the proposition of a simple condition (involving the ratio of the circumferential component of the backstress tensor and the auxiliary variable related to the isotropic hardening) to indicate when the pipe may exhibit a ratcheting behaviour, which leads to a progressive accumulation of deformation. Such kind of criterion is independent of the evolution law adopted for the backstresss tensor. Therefore, it is important to emphasize that the paper is not focused on the evaluation of the physical adequacy of different constitutive models for predicting ratcheting behaviour. Although the Marquis–Chaboche elasto-plastic constitutive Eqs. (11) and (12) have been considered in the present study, such a condition for ratcheting to arise can be applied to any cyclic plasticity model with both isotropic and kinematic hardening.

2. Summary of the elasto-plastic constitutive equations

The following set of elasto-plastic constitutive equations proposed by Marquis [12] is adequate to model the cyclic inelastic behaviour of metallic material at room temperature. A further discussion about these equations can be found in [13].

In the framework of small deformations and isothermal processes, besides the stress tensor $\underline{\underline{\sigma}}$ and the strain tensor $\underline{\underline{\varepsilon}}$, the following auxiliary variables are also considered: the plastic strain tensor $\underline{\underline{\varepsilon}}^p$, the accumulated plastic strain p and two other auxiliary variables $(\underline{\underline{X}}, Y)$, respectively related to the kinematic hardening and to the isotropic hardening. A complete set of elasto-plastic constitutive equations is given by

$$\underline{\underline{\sigma}} = \frac{\nu E}{(1+\nu)(1-2\nu)}\mathrm{tr}(\underline{\underline{\varepsilon}}-\underline{\underline{\varepsilon}}^p)\,\underline{\underline{1}} + \frac{E}{(1+\nu)}(\underline{\underline{\varepsilon}}-\underline{\underline{\varepsilon}}^p) \tag{1}$$

$$\underline{\underline{\dot{\varepsilon}}}^p = \frac{3}{2J}\left(\underline{\underline{S}}-\underline{\underline{X}}\right)\dot{p} \tag{2}$$

$$\underline{\underline{\dot{X}}} = \frac{2}{3}a\underline{\underline{\dot{\varepsilon}}}^p - b\underline{\underline{X}}\dot{p} \tag{3}$$

$$\dot{Y} = v_2(v_1+\sigma_y - Y)\dot{p} \tag{4}$$

$$\dot{p} \geq 0; \qquad F=(J-Y)\geq 0; \qquad \dot{p}F=0 \tag{5}$$

with

$$J=\sqrt{\frac{3}{2}\left(\underline{\underline{S}}-\underline{\underline{X}}\right)\cdot\left(\underline{\underline{S}}-\underline{\underline{X}}\right)} = \sqrt{\frac{3}{2}\sum_{i=1}^{3}\sum_{j=1}^{3}(S_{ij}-X_{ij})^2} \tag{6}$$

where E is the young modulus, ν the Poisson's ratio and σ_y, v_1, v_2, a, b are positive constants that characterize the plastic behaviour of the material and they can be obtained from a simple tension-compression test [14]. $\underline{\underline{1}}$ is the identity tensor, and $\mathrm{tr}(\underline{\underline{A}})$ is the trace of an arbitrary tensor $\underline{\underline{A}}$. $\underline{\underline{S}}$ is the deviatoric stress given by

$$\underline{\underline{S}} = \left[\underline{\underline{\sigma}} - \left(\frac{1}{3}\right)\mathrm{tr}(\underline{\underline{\sigma}})\underline{\underline{1}}\right] \tag{7}$$

J is the equivalent von Mises stress. $\underline{\underline{X}}$ is an auxiliary variable related to the kinematic hardening (eventually called the backstress tensor) and it is introduced to account for the anisotropy introduced by the plastic deformation. Y is an auxiliary variable related to the isotropic hardening and models how the yield stress varies with plastic deformation. p is usually called the accumulated plastic strain and $\dot{p}$ can be interpreted as a Lagrange multiplier associated to the constraint $F \leq 0$. Function F characterizes the elasticity domain and the plastic yielding surface. From Eq. (2) it is possible to affirm that

$$\dot{p} = \sqrt{\frac{2}{3}\underline{\underline{\dot{\varepsilon}}}^p\cdot\underline{\underline{\dot{\varepsilon}}}^p} \tag{8}$$

and, therefore,

$$p(t) = p(t=0) + \int_{t=0}^{t}\left(\sqrt{\frac{2}{3}\underline{\underline{\dot{\varepsilon}}}^p(\zeta)\cdot\underline{\underline{\dot{\varepsilon}}}^p(\zeta)}\right)d\zeta \tag{9}$$

If $F=J-Y<0$, it comes that $J<Y$. Hence, from the condition $\dot{p}F=0$ in (5), it is possible to conclude that $\dot{p}=0$. If $\dot{p}\neq 0$, from the condition $\dot{p}F=0$ it also comes that, necessarily, $F=0$. Besides, from Eqs. (2)–(4) it comes that, in this case, $\underline{\underline{\dot{\varepsilon}}}^p \neq$, $\neq$ and $\dot{Y}\neq 0$. Therefore, the elasto-plastic material is characterized by an elastic domain in the stress space where yielding doesn't occur ($\underline{\underline{\dot{\varepsilon}}}^p =$ = ,$\dot{p}=\dot{Y}=0$ if $F<0$).

Noting the eigenvalues of $\underline{\underline{S}}$ and $\underline{\underline{X}}$, respectively by $\{S_1,S_2,S_3\}$ and $\{X_1,X_2,X_3\}$, the elastic domain can be represented in the space of the principal directions of the deviatoric stress as a sphere centred at the point $\{X_1,X_2,X_3\}$ with radius $R=\sqrt{2/3}Y$. Generally the following initial conditions are used for a "virgin" material

$$p(t=0)=0, \quad \underline{\underline{\varepsilon}}^p(t=0)=\underline{\underline{X}}(t=0)= , \quad Y(t=0)=\sigma_y \tag{10}$$

From now on, the initial conditions **(10)** are assumed to hold in the analysis. It is also important to remark that the constitutive equations with conditions **(10)** and definition **(7)** imply that the principal directions the stress tensor, of the deviatoric stress tensor, of the plastic strain tensor and of the backstress tensor are the same.