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# Plastic failure analysis of defective pipes with creep damage under multi-loading systems

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ABSTRACT

The objective of this study is to investigate the effect of local wall thinning on the plastic limit load of modified 9Cr-1Mo steel pipe with existing creep damage based on the plastic limit load concept under high temperature. The creep damage is obtained from the Liu–Murakami creep model. A modified Ramberg–Osgood model is derived by using the relationship among the hardness, the creep damage, the yield strength and the ultimate tensile strength at high temperature to characterize the material deterioration during the creep process, where the non-uniform distribution of the material deterioration caused by the stress levels is considered. Orthogonal analysis for pipes with different type of defect under multi-loading systems are performed by using finite element method. The failure modes for pipes at limit state are revealed and the effect of local wall thinning on the plastic limit load of pipe with existing creep damage is presented. The regression formulae of the rupture time and the plastic limit load ratios for the pipes with different defect ratios and load combination ratios are established based on the numerical results. The limit loads for pipe with specified local wall thinning ratios after a period of time at high temperature can be determined conveniently through the regression formulae.

## 1. Introduction

The piping system is one of the typical structures operating at high temperature under complex loading conditions including internal pressure and bending moment in nuclear-fuelled or fossil fired power plants and petrochemical industries. In operation, pipes can contain flaw of specified sizes, which can be detected during in-service inspection. One type of flaw is the blunt flaw of local wall thinning which can be induced by erosion, corrosion, mechanical damage and crack polishing [1]. Such a defect in piping component could reduce the load-carrying capacity and lead to some accidents of leaks and explosions. Therefore, evaluating the effect of local wall thinning on the maximum load-carry capacity is crucial for the safe operation of industrial infrastructures.

To assess the safety and integrity of the structures containing local wall thinning defect, the limit analysis is an effective approach [2,3]. In the past decades, the limit analysis has been widely used and extended in many fields, such as the 2-D geometries based on the non-linear mathematical programming [4–7], the finite element method [8–10], the elastic or modified compensation method [11,12] and the boundary element method [13], the defective pipeline and 3-D structure based on the dimension reduced iteration method [14], the penalty-duality algorithm and direct iteration method [2,3] and the linear matching method (LMM) [15,16], the thick-walled cylinders with surface or circumferential defect based on the finite element method (FEM) [17,18], the experiment and FEM based limit analysis for the straight pipes or pipe elbows subjected to complex loads such as the internal pressure [19–21], bending moment [22–24], torsion moment [25] and their combinations [26–29], and the references therein. A series of reasonable and meaningful limit load results have been obtained and many national standards and code cases have been developed based on the research achievements [30–34]. With pipes being widely used in the high temperature field, the effect of high temperature and even creep failure has been considered in some design codes [30, 35].

There are two main differences for the limit load analysis of the pipes at high temperature comparing with that at room temperature [36]. First, the creep regime must be considered for the components subjected to high temperature, while the creep behavior is always ignored at room temperature. For attempting to characterize the full creep curve and the creep damage, the continuum damage mechanics (CDM) models coupling with creep, plasticity and viscoplasticity have been developed by several researchers based on the micro mechanism [37–39] or the phenomenological approaches such as the Kachanov–Rabotnov model (K–R model) [40,41], the Chaboche and Lemaitre model [42,43], the Liu–Murakami model (L–M model) [44,45] and the Dyson model [46]. The CDM creep models also have been used in the researches of the

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structures mechanical behaviors at high temperature concerning with the simulation of creep crack growth [47,48], the life prediction of the components with crack-like defect [49], the creep failure life prediction of P91 pipes [50,51] and the damage assessment method of P91 steel welded tube [52] and so on. Second, for the limit analysis at room temperature, the material property is defined as the virgin state and the elastoplastic constitutive relation is used to calculate the limit load. However, at high temperature, the creep damage can lead to the cavity nucleation and growth in microscale [37], which could lead to the reduction of effective load-bearing area of engineering structures in macroscale. In other word, the material deterioration is happened at high temperature. Researches show that the yield strength (YS) and the ultimate tensile strength (UTS) will be reduced with the increasing of creep damage [53–56], which means the material deterioration can be characterized by creep damage. Consequently, the plastic limit load will be decreased correspondingly for the structures serviced at high temperature for a long time. It can also be revealed that the plastic limit load at high temperature is dependent on creep time when the material deterioration is considered into the limit analysis. Recently, some researches about the plastic limit load of the structures with defect at high temperature have been conducted, such as the 2.25Cr-1Mo steel pressure vessel containing volume defect considering reduced yield stresses factors [53], the P91 pipe with local wall thinning defect considering the K–R damage factor [54], the pressure vessel containing volume defect considering damage factor of Basirat model [55] and the P91 pressure vessel containing volume defect by means of Liu–Murakami creep damage model [36].

It should be pointed out that the creep damage accumulation is dependent on the stress level [50,51]. However, due to the local wall thinning in engineering structures, the stress level can distribute gradually along the defect, which is quite different from the response of uniform specimens. Caused by the non-uniform distribution of the stress level, the creep damage field varies in the structures. Therefore, the material deterioration characterized by the creep damage also distributes unequally in the structure, especially at the defect region, which could affect the limit load of the structures and was not attracted sufficient attention yet.

The objective of the present study is to systematically investigate the effect of local wall thinning on plastic limit load of pipe with existing creep damage under a combined internal pressure and bending moment considering the non-uniform distribution of the material deterioration caused by the different stress levels. The paper is structured as follows. Section 2 briefly introduces the modified Ramberg–Osgood (R–O) model conjunction with the Liu–Murakami (L–M) creep damage model. In Section 3, the definition and determination of the plastic limit load at high temperature and the numerical procedure of the limit analysis are introduced. The finite element model for pipes with local wall thinning defect is presented in Section 4. The numerical results and discussions for the effect of local wall thinning on the limit load of pipe at high temperature are presented in Section 5, and the study is concluded in Section 6.

## 2. Theoretical background

The relationship between the L–M creep damage model and the modified R–O model by means of the hardness ratio to characterise the material behavior at high temperture has been established in the previous work [36], and for the integrity of this paper, a brief introduction is given highlighting the details necessary.

### 2.1. Liu–Murakami model

At high temperature, the creep deformation plays a significant role in mechanical behavior and the stress redistribution is found to be dependent on the creep constitutive laws [57]. A coupled creep/damage model with single damage variable proposed by Liu and Murakami [44] is used to predict the creep damage in the pipe models. The multiaxial form of the L–M model is given by Liu and Murakami [44]

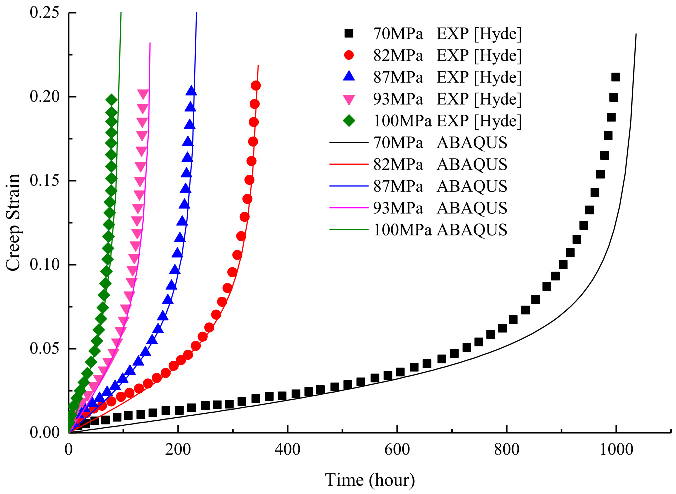

**Fig. 1.** Uniaxial creep validation of finite element analyses [36].

$$\dot{\varepsilon}_{ij}^{c} = \frac{3}{2} A \sigma_{eq}^{n-1} S_{ij} e^{\frac{2(n+1)\sigma_1^2 \omega^{3/2}}{\pi\sqrt{1+3/n}\sigma_{eq}^2}} \tag{1}$$

$$\dot{\omega} = \frac{B(1-e^{-q_2})}{q_2} \sigma_r^{\chi} e^{q_2 \omega} \tag{2}$$

where $\varepsilon_{ij}^{c}$, $\sigma_{eq}$ and $S_{ij}$ are the multiaxial creep strain components, von Mises equivalent stress, and deviatoric stress components, respectively. $\dot{()}$ represents the temporal derivative. The damage parameter $\omega$ represents the extent of material deterioration in creep regime, which varies from 0.0 to 1.0 indicating virgin material and fully damaged material respectively. $A$, $B$, $n$, $\chi$ and $q_2$ are material constants describing secondary and tertiary creep stages. And $\sigma_r$ is the rupture stress defined by Hayhurst et al. [58]

$$\sigma_r = \alpha\sigma_1 + (1-\alpha)\sigma_{eq} \tag{3}$$

where the triaxial stress state material constant, $\alpha (0 \le \alpha \le 1)$, determines the value of the rupture stress by quantifying the contribution of the maximum principle stress $\sigma_1$.

The creep life fraction function of L–M model is given by Du et al. [36]

$$\frac{t}{t_r} = \frac{1-e^{-q_2\omega}}{1-e^{-q_2}} \tag{4}$$

The finite element method based creep deformation analysis has been carried out by using the commercial codes ABAQUS [59]. The subroutine is verified through the uniaxial creep tests [51], which is plotted in Fig. 1. The compositions of the chemical components for the modified 9Cr-1Mo steel at 650 °C are listed in Table 1 [51]. All the constant parameters for the L–M model are listed in Table 2 [60].

### 2.2. Modified Ramberg–Osgood model considering creep damage

The R–O equation [61] is an elastoplastic constitutive model with an exponent law and has been widely used to describe the stress–strain curve of ductile material with general hardening behavior. Hence, the R–O model is employed for the modified 9Cr-1Mo steel and the equation is given as

$$\varepsilon = \varepsilon_e + \varepsilon_p = \frac{\sigma}{E} + \left(\frac{\sigma}{H_{RO}}\right)^{\frac{1}{n_{RO}}} \tag{5}$$

where $\varepsilon$, $\varepsilon_e$, $\varepsilon_p$ and $E$ are the total strain, the elastic strain, the plastic strain and the Young's module, respectively. $n_{RO}$ is the hardening