International Journal of Mining Science and Technology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

A fatigue damage model for rock salt considering the effects of loading frequency and amplitude

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ARTICLE INFO

Article history:
Received 2 December 2015
Received in revised form 16 January 2016
Accepted 28 March 2016
Available online xxxx

Keywords:
Rock salt
Fatigue
Frequency
Stress amplitude
Damage

ABSTRACT

With the large-scale construction of underground gas storage in salt deposit, much more efforts have been made to assess the fatigue properties of rock salt. The fatigue damage processes the primary, steady, and accelerated phases, which is similar to the axial irrecoverable deformation compiled from the loci of the loading cycles of rock salt. The cumulative fatigue damage increases with a decrease in the loading frequency and with an increase in the stress amplitude within the range tested. To take into account the effects of loading frequency and amplitude on the fatigue behavior of rock salt subjected to cyclic loading, a low cycle fatigue damage model was exclusively established combined with the Manson–Coffin formula. The proposed damage evolution equation was validated with experimental results and proved to be efficient in the prediction of fatigue damage tendency of rock salt under different loading frequencies and amplitudes.

1. Introduction

In recent years, more and more solution-mined salt caverns are being utilized for natural gas storage and compressed air energy storage (CAES). The base rock surrounding salt cavity is subjected to cycles of loading resulting from the fluctuation of internal pressures during product injection and withdrawal periods. Therefore, the fatigue strength and deformation characteristics of rock salt under dynamic cyclic loading play an important role in the long-term stability of salt caverns. Although the mechanical behavior of rock salt subjected to static or monotonic loads has long been recognized, relevant researches on fatigue damage properties of rock salt are insufficient [1–7]. It is well known that the fatigue properties of rock salt depend on the maximum stress, amplitude, loading frequency and waveform, etc. [8–11]. The deformation behavior of salt under cyclic loading is similar to that of static creep tests [8]. The salt elastic modulus decreases with loading cycles as a power function and drives to a constant until failure [9]. The fatigue life of salt specimen decreases with an increase in maximum stress, stress amplitude, or mean stress [10,11].

Fatigue is considered to be the process of damage accumulation of a material under cyclic loading. The fatigue damage can be reflected by various damage variables (e.g. elastic modulus, residual strain, ultrasonic wave velocity, and energy dissipation). Xiao et al. proposed an inverted S-shaped nonlinear fatigue damage cumulative model based on the deformation law of axial irreversible deformation [12]. Li et al. suggested a new damage variable expression and low-cycle fatigue damage equation considering strain hardening characteristic for rock material in fatigue stress [13]. Zhao studied the fatigue damage evolution of rock salt with a low-cycle fatigue damage model suggested by Lemaitre [14].

The aforementioned works mainly focus on the experimental investigation of the effects of the maximum stress, amplitude on the fatigue property, while neglecting the influence of loading frequency. An effort, therefore, has been made through this theoretical study to reveal the effects of frequency and stress amplitude on fatigue damage evolution of rock salt under cyclic loading.

2. Low cycle fatigue damage model

It is well known that fatigue damage results from accumulative plastic strain. There is commonly a three-stage irreversible deformation of rock under cyclic loading as shown in Fig. 1. In the initial phase, the previously existing micro pores and cracks will close when the rock is compressed, and the plastic deformation increases rapidly; in the steady phase, the development of micro

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http://dx.doi.org/10.1016/j.ijmst.2016.05.054
2095-2686/© 2016 Published by Elsevier B.V. on behalf of China University of Mining & Technology.

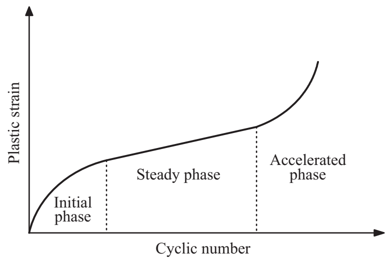

Fig. 1. Development of irreversible deformation of rock under cyclic loading.

cracks is stable and the plastic deformation increases with a constant rate; in the accelerated phase, cracks propagate unstably and eventually converge, resulting in the failure, which corresponds to the development of plastic deformation until failure. Therefore, the accumulative plastic strain is chosen to characterize the internal damage, which is defined as:

$$D = \frac{\varepsilon_p}{\varepsilon_f} \tag{1}$$

where ε_p is the accumulated plastic strain; and ε_f the ultimate plastic strain.

The classic Ramberg–Osgood rule is used to describe the strain hardening behavior of rock salt under cyclic loading

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{k}\right)^{1/n} \tag{2}$$

where k is the hardening coefficient; and n the hardening index.

Hence, the relationship between stress increment and plastic strain increment for each cycle can be given as follows

$$\Delta\varepsilon_p = \left(\frac{\Delta\sigma}{k}\right)^{1/n} \tag{3}$$

By introducing effective stress $\Delta\bar{\sigma} = \frac{\Delta\sigma}{1-D}$, Eq. (3) can be rewritten as

$$\Delta\varepsilon_p = \left[\frac{\Delta\sigma}{k(1-D)}\right]^{1/n} \tag{4}$$

By combining Eqs. (1) and (4), the fatigue damage increment per each cycle is

$$\frac{\delta D}{\delta N} = \frac{\Delta\varepsilon_p}{\varepsilon_f} = \frac{1}{\varepsilon_f}\left[\frac{\Delta\sigma}{k(1-D)}\right]^{1/n} \tag{5}$$

where N is the cyclic number.

Eq. (5) can be transformed into

$$(1-D)^{1/n} dD = \left(\frac{\Delta\sigma}{k}\right)^{1/n} \frac{1}{\varepsilon_f} dN \tag{6}$$

The cyclic stress–strain curve of salt develops in a mode of "sparse-dense-sparse", which indicates that the hardening coefficient is variable in three-phase deformation. The hardening coefficient is assumed to change with stress amplitude and loading cycle as a power function

$$k = (\Delta\sigma)^m N^r \tag{7}$$

Substitute Eqs. (7) into (6), we have

$$\int_{D_0}^{D} (1-D)^{1/n} dD = \int_0^N \left(\frac{\Delta\sigma^{1-m}}{N^r}\right)^{1/n} \frac{1}{\varepsilon_f} dN \tag{8}$$

By integrating Eq. (8), it yields

$$(1-D_0)^{1+1/n} - (1-D)^{1+1/n} = \frac{1+n}{n-r}\frac{N^{1-r/n}}{\varepsilon_f}(\Delta\sigma)^{(1-m)/n} \tag{9}$$

According to Manson–Coffin experiential formula, the total strain can be also divided into elastic and plastic parts as follows [15]:

$$\varepsilon = \varepsilon_e + \varepsilon_p = c_1\left(N_f f^{k_1-1}\right)^{-\beta_1} + c_2\left(N_f f^{k_2-1}\right)^{-\beta_2} \tag{10}$$

where f is the frequency; c_1, c_2, k_1, k_2, β_1, and β_2 the material constants; ε_e and ε_p the respectively elastic strain and plastic strain; and N_f the specimen life.

Therefore, the relationship between loading frequency and ultimate plastic strain can be represented by

$$\varepsilon_f = c_2\left(N_f f^{k_2-1}\right)^{-\beta_2} \tag{11}$$

Substitute Eqs. (11) into (9), it yields

$$(1-D_0)^{1+1/n} - (1-D)^{1+1/n} = \frac{1+n}{n-r}\frac{N^{1-r/n}}{c_2\left(N_f f^{k_2-1}\right)^{-\beta_2}}(\Delta\sigma)^{(1-m)/n} \tag{12}$$

To simply formula expression, let $1 - r/n = -\beta_2 = \beta$, $-\beta_2(k_2 - 1) = b$, Eq. (12) reduces to

$$(1-D_0)^{1+1/n} - (1-D)^{1+1/n} = \frac{1+n}{n-r}\frac{(\Delta\sigma)^{(1-m)/n}}{c_2 f^b}\left(\frac{N}{N_f}\right)^{\beta} \tag{13}$$

Given the initial condition $D_0 = 0$, then

$$D = 1 - \left[1 - \frac{1+n}{n-r}\frac{(\Delta\sigma)^{(1-m)/n}}{c_2 f^b}\left(\frac{N}{N_f}\right)^{\beta}\right]^{\frac{n}{1+n}} \tag{14}$$

Let $(1 + n)/c_2/(n - r) = a$, we have

$$D = 1 - \left[1 - a\frac{(\Delta\sigma)^{(1-m)/n}}{f^b}\left(\frac{N}{N_f}\right)^{\beta}\right]^{\frac{n}{1+n}} \tag{15}$$

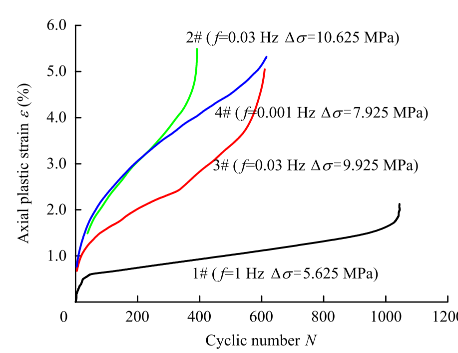

Fig. 2. Axial plastic strain vs. cyclic number.

Table 1
Experimental scheme of cyclic loading for rock salt specimen.

Specimen	Test equipment	Maximum stress σ_{max} (MPa)	Minimum stress σ_{min} (MPa)	Stress amplitude $\Delta\sigma$ (MPa)	Frequency f (Hz)
1#	RMT-150B	22.5	11.25	5.625	1.000
2#	UTM	21.4	0.15	10.625	0.030
3#		20.0	0.15	9.925	0.030
4#		16.0	0.15	7.925	0.001

Please cite this article in press as: Wang Y et al. A fatigue damage model for rock salt considering the effects of loading frequency and amplitude. Int J Min Sci Technol (2016), http://dx.doi.org/10.1016/j.ijmst.2016.05.054