International Journal of Rock Mechanics & Mining Sciences 72 (2014) 71–79

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

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

Scaling of fatigue crack growth in rock

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ARTICLE INFO

Article history:
Received 26 November 2013
Received in revised form
29 July 2014
Accepted 18 August 2014

Keywords:
Cyclic loading
Sandstone
Size effect
Fatigue kinetics
Fracture process zone

ABSTRACT

This paper presents a comprehensive set of size effect experiments on fatigue crack kinetics for Berea sandstone. It is observed that for all specimens the Paris-Erdogan law is applicable for a wide range of amplitudes of the stress intensity factor. The fatigue tests also indicate that there is a small-crack growth regime at the beginning stage of cyclic loading, where the growth rate decreases as the crack initiates from the notch tip. It is shown that the fracture kinetics for both the small-crack growth and the Paris regimes is subjected to a strong size effect. Meanwhile, a series of size effect tests on monotonic strength of Berea sandstone is also performed in order to investigate the difference in fracture process between fatigue and monotonic loading scenarios. By using the digital image correlation method, it is found that the fracture process zone (FPZ) length under cyclic loading is about 60% larger than that under monotonic loading. In parallel with the experimental investigation, it is shown that the observed effect of the specimen size on the fracture kinetics can be explained by a size effect model for the critical energy dissipation for fatigue crack growth, which is analogous to the size effect on the apparent fracture energy for monotonic loading.

1. Introduction

Geological materials are often subjected to repeated loading from various sources, such as thermal cycles and periodic underground gas injection and extraction. Such cyclic loads could lead to subcritical crack growth and eventually cause a significant decrease in material strength and a catastrophic failure. Therefore, understanding the mechanical behavior of rock under cyclic loading is critical for ensuring the safety of underground structures. Considerable efforts have been devoted to investigating the overall effect of cyclic loading on the strength and fracture toughness of rock [1–9]. Nevertheless, there is a limited amount of research that focuses on the fracture kinetics of rock under cyclic loading [10,11]. As a comparison, it is interesting to note that fracture kinetics has been studied for static fatigue of rock, which provides an improved understanding on rock damage under creep loading [12–14].

The most well-known kinetics equation for fatigue crack growth is probably the Paris-Erdogan law [15], which expresses the rate of fatigue crack growth as a power-law function of the amplitude of the stress intensity factor (SIF):

$$\frac{da}{dN}=A\Delta K^{n} \tag{1}$$

where a = crack length, N = number of cycles, A, n = constants, and ΔK = SIF amplitude. Constant A depends on the ratio between the minimum and maximum SIFs, commonly referred to as the R-ratio. The Paris-Erdogan law was initially proposed for metals based on experimental observations, and it has been shown that for metals this power-law function can be justified by a damage accumulation model of tensile yielding or slip in the reversed plastic zone at the crack tip [16,17]. At the same time, it is widely agreed that the Paris-Erdogan law is valid for a wide range of ΔK from ΔK_{th}, a threshold value where no crack growth is observed, to the maximum limit corresponding to fast fracture. Various attempts have been made to modify the Paris-Erdogan law so that it can cover the entire range of SIF amplitudes. However, for most engineering applications, the applied cyclic SIF usually falls in the intermediate range where the Paris-Erdogan law is valid.

Extensive experimental studies have shown that the Paris-Erdogan law is also applicable to brittle and quasibrittle materials such as ceramics [18–21] and concrete [22,23], except that the value of the power-law exponent n is much higher than that for metals. In a recent study [24], the Paris-Erdogan law was physically justified for brittle and quasibrittle materials based on atomic fracture mechanics and an energetic analysis, which relates the fatigue kinetics of a macrocrack to the growth rate of nanocracks that are in the cyclic fracture process zone (FPZ) of the macrocrack. Nevertheless, very limited amount of studies have been performed to verify the applicability of the Paris-Erdogan law for rock.

Another important aspect of fatigue kinetics is its dependence on the specimen size [25,23,26–29]. Understanding such a scale effect for rock is essential since the actual rock mass is usually much larger than the specimens used in laboratory experiments.

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http://dx.doi.org/10.1016/j.ijrmms.2014.08.015
1365-1609/

The existing theoretical framework for the scale effect on the fatigue kinetics is largely based on the argument of incomplete similarity, where the detailed form of the scaling function cannot directly be obtained [25,26,28,29]. Bažant and co-workers [22,23] proposed to normalize the Paris-Erdogan law by the apparent fracture toughness of the material, from which a size effect on the Paris-Erdogan law can be obtained based on the size dependence of the apparent fracture toughness. Nevertheless, it was found that the direct use of the size effect on the apparent fracture toughness cannot describe the observed size effect on the Paris-Erdogan law for concrete, and therefore the rationale behind such normalization needs further justification. This paper presents a systematic experimental investigation on the fatigue kinetics of Berea sandstone. Based on the experimental observations, a theoretical model for the size-dependence of fatigue kinetics is developed.

2. Experimental investigation

In this study, we performed a set of experiments on Berea sandstone to investigate the effect of specimen size on crack growth under cyclic loading. In addition to fatigue tests, we also conducted monotonic strength tests on geometrically similar specimens of different sizes in order to compare the size effect on fatigue kinetics with that on monotonic strength. Berea sandstone is light gray in color, and it consists of quartz grains from 0.1 to 0.8 mm, with an average grain size of 0.2 mm. The tested material is homogeneous but slightly anisotropic in elastic response, exhibiting a variation of 5% in P-wave velocities.

The specimens were cut from one block of sandstone, positioned so that crack propagation was perpendicular to bedding, using a diamond blade saw that was water cooled; the specimens were then notched at mid-span with another diamond blade producing a notch radius of 1 mm and a notch depth of 20% the beam depth (height). The beams were precision ground to establish a uniform depth within 0.1 mm and placed in a 60°C oven overnight to remove moisture. Testing was performed at room temperature (20°C) and humidity (50% RH). All beams have a depth-to-span ratio of 1:2.5. For both monotonic and fatigue tests, geometrically similar specimens of a size ratio 1: 2: 4 were prepared; the smallest beam has a depth of 25.4 mm and the largest beam has a depth of 101.6 mm. Since we are interested in 2D scaling, the width (thickness) of the beam was kept constant for all beam sizes, i.e. $b=20$ mm (Fig. 1), which avoids the secondary effects of the transition from the interior (plane strain) to the free face (plane stress) along the crack front.

Both monotonic and fatigue tests were conducted on three-point bend beams within a closed-loop, servo-hydraulic load frame. A clip gauge, which measures the crack mouth opening displacement (CMOD) denoted by δ_m, was attached at the notch mouth between two steel clips glued to the bottom fiber of the beam. For the monotonic strength tests, the specimens were loaded by CMOD at a rate of 2×10^{-4} mm/s so that the crack would propagate in a controlled manner and the post-peak behavior could be captured. For fatigue tests, we applied a cyclic load on the specimens with a loading frequency of 1 Hz, where the maximum and minimum loads were kept to be approximately 75% and 3% of the monotonic load capacity, respectively, which was measured from the monotonic strength tests (i.e. the R-ratio is about 4% for all specimens), and the CMOD was measured throughout the entire loading duration.

During the experiments, we used the digital image correlation (DIC) technique to examine the fracture processes at initiation and propagation. DIC is a particle-tracking technique that uses digital images to generate displacement fields [30–33]. To implement DIC, we coated the surface of the specimens with white paint and when dry, lightly spray black paint to create speckles. As the specimen deforms, the speckles move and the surface displacement can be tracked by evaluating their movement. A charge-coupled device (CCD) camera was attached to a fixed frame, and during load application, pictures were taken of a 36×48 mm region surrounding the notch. A commercial DIC software package (DaVis) was used to analyze the pictures for computing the corresponding displacement fields. Further details are contained in [33].

2.1. Size effect test on monotonic strength

We first performed the size effect test on the monotonic strength of the beams. Fig. 2 presents the measured load–CMOD curves for specimens of all three sizes. It can be seen that as the specimen size increases the post-peak regime of the load–CMOD curves becomes steeper, which signifies a more brittle failure behavior. Such a size-dependent failure response is a common feature of quasibrittle structures, which further leads to a size effect on the nominal structural strength [34–36]. Here we define the nominal strength of the beam simply as $\sigma_N=P_{\max}/bD$, where P_{max}=maximum load that the beam can sustain, D=characteristic size of the beam to be scaled (here we choose D as the beam depth), and b=width of the beam in the transverse direction. Fig. 3 shows the measured relationship between σ_N and specimen size D. As seen, although with a limited size range (i.e. 1: 2: 4), we observe a marked size effect on σ_N, and this size effect can be well fitted by the energetic size effect equation [37,34,27]:

$$\sigma_N=\sigma_0(1+D/D_{0m})^{-1/2} \tag{2}$$

where

$$\sigma_0=\sqrt{EG_{f\infty}/c_f g'(\alpha_0)} \tag{3}$$

$$D_{0m}=c_f g'(\alpha_0)/g(\alpha_0) \tag{4}$$

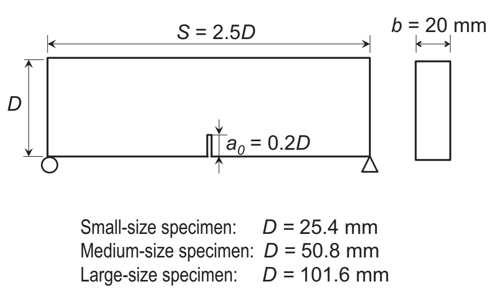

Fig. 1. Geometry of test specimens.

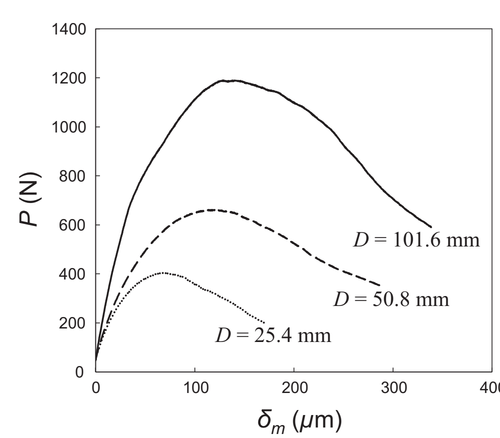

Fig. 2. Measured load–CMOD curves in strength tests.