Effect of Micro-Structure on Fatigue Behavior of Intact Rocks under Completely Reversed Loading

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Abstract

Rock formations and structures can be subjected to both static and dynamic loadings. Static loadings resulting from different sources such as gravity and tectonic forces and dynamic forces are intermittently transmitted via vibrations of the earth’s crust, through major earthquakes, rock bursts, rock blasting and drilling and also, traffic. Reaction of rocks to cyclic and repetitive stresses resulting from dynamic loads has been generally neglected with the exception of a few rather limited studies. In this study, , two crystalline quarry stones in Iran; (Natanz gabbro and Green onyx) and one non-crystalline rock (Asmari limestone) are used to evaluate the effect of micro-structure of intact rock on fatigue behavior. These rocks have different mineral compositions and formation conditions. A new apparatus based on rotating beam fatigue testing machine (R.R.Moore), which is commonly used for laboratory fatigue test in metals, is developed and fatigue behavior and existence of the endurance limit were evaluated for the mentioned rocks based on stress-life method. The obtained results in the variation of applied amplitude stress versus loading cycle number (S-N diagram) followed common relationship in other materials. In addition, the endurance limit is perceived for all tested rocks. The results also illustrated that the endurance limits for all types of tested rocks in this study are ranged between 0.4 and 0.6 of their tensile strengths. The endurance limit to tensile strength fraction of green onyx and Natanz gabbro were approximated in a higher value compared to the Asmari limestone with non-crystalline micro-structure.

1. INTRODUCTION

Cyclic loading often causes a material to fail prematurely at a stress level less than is determined strength under monotonic condition. This phenomenon is commonly known as “fatigue” [1]. The word "fatigue" was introduced in the 1840s and 1850s to describe failures occurring due to a cyclic loading on a material. In Germany during the 1850s and 1860s, Wöhler performed many laboratory fatigue tests under repeated stresses. These experiments were concerned with railway axle failures and are considered to be the first systematic investigation of fatigue. Thus, Wöhler has been called the "father" of systematic fatigue testing. Using stress versus life (S-N) diagrams, he showed how fatigue life decreases with higher stress amplitudes and that below a certain stress amplitude, and the specimens do not fail. Thus, Wöhler introduced the concept of the S-N diagram and the endurance limit [2-4]. Fatigue failure occurs with the occurrence of three important conditions: (a) a sufficiently high value of maximum stress, (b) a large enough variation or fluctuation in the applied stress (stress amplitude), and (c) a sufficiently large number of cycles of the stress [5].

Rock formations and structures can be subjected to both static and dynamic loads. Static loads result from different sources such as tectonic and gravity forces and dynamic forces are intermittently applied vibrations of the earth’s crust, through major earthquakes, rock bursts, rock blasting and drilling and also traffic [6]. In reality, most structures in their lifetime experience fluctuating loadings due to change in the magnitude, direction and point of applied loads [3].

Reaction of rocks to cyclic and repetitive stresses resulting from dynamic loads has been generally neglected with the exception of a few rather limited studies [1; 6-32]. One of the first comprehensive studies on the cyclic fatigue behavior of rock was conducted on the Berea sandstone at compression stress range. The results showed that the rock strength is decreased up to 24 percent due to repetitive compressive loading. Also the rocks with smaller grain size have comparatively higher strength [7].

The effect of cyclic compressive loading on reduction in strength, Young's modulus, compressive strength, Poisson's ratio and dynamic strength of rocks has been reported in previous studies [6-8; 11; 20; 21; 24; 25]. Moreover, shear cyclic loading may decrease shear strength of rock joints [13; 17]. The influence of indirect tensile cyclic loading using pre-cracked specimens has been investigated and showed that the failure load in cyclic loading tests decreases compared with the relative values obtained under static loading tests [26; 27].

Most previously reported research works related to the evaluation of fatigue behavior of rocks focused on cyclic compression loading. However, fatigue failure appears to be a class of tensile failure, or induced by tensile stress [2-4]. In other words, if tensile stress decreases during a specific loading process, fatigue failure experiences reduction as well [2-4]. Even though the external loading may be compressive, fatigue cracks may grow due to the presence of residual tensile stress fields near stress concentrators. In terms of fully compressive cyclic loading, fracture mechanics approach does not predict fatigue damage [4; 33]. Notwithstanding the propagation of fatigue cracks under cyclic compressive loading in practice, compression-compression loading is of a relatively prolonged fatigue life in relation to tension-tension loading. [34].

The three major fatigue life analysis methods are the stress-life method, the strain-life method, and the linear-elastic fracture mechanics method. These methods attempt to predict the life in number of cycles to failure for a specific level of loading. Equation (1) (known as the Basquin relation) represents the typical Stress (S) –fatigue life (N) in stress-life method:

$$S = A(2N)^B \tag{1}$$

Where, A is the fatigue strength coefficient and $\boldsymbol{B}$ is the fatigue strength exponent. There are also other S–N expressions, which the Wöhler relation is one of the most widely used equation [4]. In the strain-life method, the relation of the total strain amplitude (ε_a) and the fatigue life in reversals to failure ($2N_f$) can be expressed in the following form:

$$\varepsilon_a = \frac{\sigma_f}{E}\left(2N_f\right)^b + \varepsilon_f\left(2N_f\right)^c \tag{2}$$

where, σ_f is fatigue strength coefficient, E is young modulus, b is fatigue strength exponent, ε_f is fatigue ductility coefficient and c is fatigue ductility exponent [2]. Linear elastic fracture mechanics has been successfully used to model the fatigue crack growth behavior. Based on this method, under a loading condition with the stress range ΔS , the number of cycles N_{if} for crack propagation from the initial crack length a_i to the final crack length a_f can be evaluated as follow:

$$N_{if} = \frac{\left(1-\left(\dfrac{a_i}{a_f}\right)^{\frac{m}{2}-1}\right)}{C\left(F\Delta S\sqrt{\pi}\right)^m\left(\dfrac{m}{2}-1\right)a_i^{\frac{m}{2}-1}} \tag{3}$$

where, F represents the function depending on the geometries and loading condition and C and m are the material constants [3]. Since the stress-life method is the most traditional method which is the easiest to implement for a wide range of design applications [3; 4], this research is planed based on stress-life method.

In this study, for evaluating effect of micro-structure on fatigue behavior of intact rock, two crystalline quarry stones in Iran; (Natanz gabbro and Green onyx) and one non-crystalline rock (Asmari limestone) are used which have different mineral compositions and formation conditions. A new apparatus based on rotating beam fatigue testing machine (R.R.Moore [35]), which is commonly used for laboratory fatigue test in metals, is developed and all types of rocks were subjected to a completely reversed loading condition to evaluate fatigue behavior and existence of the endurance limit of mentioned rocks based on stress-life method.

2. LABORATORY TEST SETUP

The S-N diagram generally is obtained by completely reversed stress cycles in which the stress varies between a same magnitude of tension and compression levels. The R. R. Moore rotating-beam machine [35] is often utilized to apply pure bending to specimens based on their weights [3; 36]. Completely reversed state denotes a type of loading which alternates around a zero mean stress. The stress-life fatigue tests are typically carried out on several identically prepared specimens at different completely reversed stress amplitudes [2]. The first test is performed at a stress level slightly smaller than the ultimate tensile strength of the material while the second test is conducted at a stress level less than that used in the first step. This process is continued, and the results of applied stress and loading cycles are plotted as an S-N diagram. This chart may be plotted on a semi or full log paper [2]. The completely reversed loading condition can be introduced by combination of pure bending and rotation (Figure 1). As can be seen, bending stress (σ) depends on applied bending moment (M), distance from the neutral axis (y) and the second moment of area about the neutral axis (I) as follows,

$$\sigma = \frac{My}{I} = \frac{FLy}{I} \quad (4)$$

where F is the applied force by means of weights, L is the specimen length. When the specimen rotates, "y" changes in range $[-R,+R]$ depending on the rotation frequency (ν) and time (t) and so, each point experiences one completely reversed loading which is characterized with stress amplitude (σ_a) as follows,

$$\sigma_a = \frac{FRL}{I} COS(2\pi\nu t) \quad (5)$$

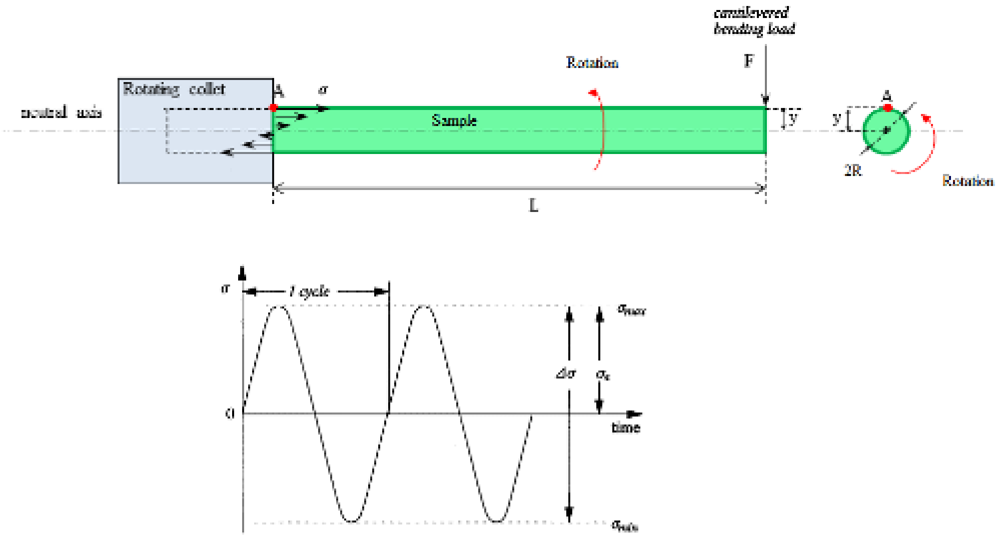

Figure 1. Generating completely reversed loading by combination of rotation and bending load [3]

2.1. Preparation of rock specimens

The theory and testing machine which used in this study were inspired from metals. In addition the micro-structure of metals and crystalline rocks have some similarities and differences, so the micro-structure is selected as research objective. Two frequently used crystalline quarry stones in Iran (Natanz gabbro and Green onyx) and one non-crystalline rock (Asmari limestone) were used as the basis samples in this research work. Although Natanz gabbro and Green onyx samples are known as crystalline rocks, however Natanz gabbro is completely different from Green onyx in mineral composition and formation. Natanz gabbro (Figure 2 (a)) is an intrusive igneous rock which is slightly altered and consisted of 61% feldspar (plagioclase), 31.5% clinopyroxene, 2% chlorite and 1.5% opaque minerals[37] . Green onyx (Figure 2 (b)) is a metamorphic rock made almost entirely of calcite[38] and Asmari limestone (Figure 2 (c)) as sedimentary rock is consisted of 62% dolomite, 24% calcite, 9% siderite and 5% silica [39].

The microscopic inspections of Natanz gabbro show some alteration of amphiboles and feldspars into chlorite (see Figure 2 (a)) and chlorite are scattered in the spaces between other minerals[38]. This alteration can be justified by reducing uniaxial compressive strength of Natanz gabbro from the anticipated value. The microscopic images confirm that Green onyx have fine-gained, dense and uniform structure which made of almost entirely calcite minerals. Asmari limestone have a very fine-grained composition containing carbonaceous matrix and fossil remains that details are not too clear under microscope. The measured characteristic parameters of rocks that used in this study are presented in Table 1.

A number of cylindrical specimens (core specimens) with the length of 120 mm, and the diameter of 11 mm were prepared by using rotary drilling machine. All specimens were fixed with two metal caps. Since most of the fatigue cracks extended from the surface of the specimens, surface polishing had a significant effect on the fatigue strength of the specimens [3]. In order to mitigate the effects of surface roughness on the geometric stress concentration, the sample surfaces were polished carefully. The steps of preparation of specimens are shown in Figure 3.

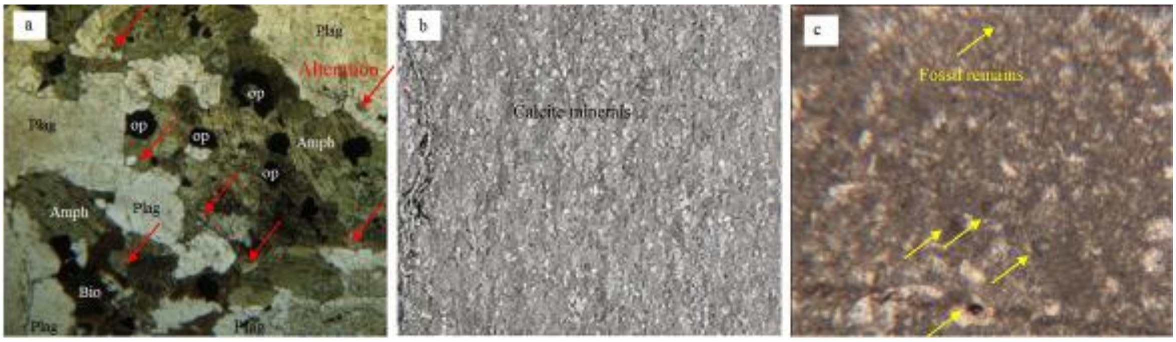

Figure 2. Plane-polarized photomicrograph of a) Natanz gabbro b) Green onyx c) Asmari limestone

Table 1. Characteristic parameters of specimens

Rock type	Young's modulus (GPa)	Uniaxial compressive strength (MPa)	Brazilian Tensile strength (MPa)	Average grain diameter (mm)
Natanz gabbro	78	75.5	10.8	0.75
Green onyx	96	100.6	7.4	0.03
Asmari Limestone	21.1	102.9	8.1	Non-crystalline

a b c

Figure 3. a) Sampling of Green onyx b) prepared core specimens of Natanz gabbro and c) prepared specimens of Asmari limestone

2.2. Test Apparatus

The fatigue-testing machine was designed and fabricated for the aforementioned purpose. This testing machine was inspired by R.R.Moore testing machine [35]. The configuration of the test machine is shown in Figure 4. The machine can set the rotation speed of specimens (frequency of loading) between 100 and 1200 Round per Minute (RPM). It is also equipped with a sensor that automatically stops the operation upon the failures occurring and records the number of cycles. The incorporated sensor and counter are capable of counting the number of performing cycles accurately even at 5000 RPM. The loading type is a completely reversed sinusoidal loading.

2.3. Performing the Test

Totally, five specimens of each rock samples were subjected to static loading to determine average tensile strength under bending condition. The determined ultimate tensile strength was 28MPa, 18.1MPa and 23.5MPa for Natanz gabbro, Green onyx and Asmari limestone, respectively. The cyclic loading tests are performed based on presented model in section 2. The loading frequency kept constant 5Hz for all fatigue test.

Figure 4. Rotating rock beam fatigue test machine

Since there would be some initial defects in some specimens, some of the test data cannot be considered in the final analyses. It is obvious that the maximum bending stress occurred at the end of the specimens and therefore, the acceptability of the results was contingent upon failure location. When a specimen failed, the location of the failure was inspected. For instance, the specimen shown in Figure 5 (a) had experienced failure at an unexpected location which could have been induced by preexisting micro fractures/flaws. Thus, a negligible portion of the data were omitted from the final analyses. Some acceptable broken specimens after the fatigue test are shown in Figure 5 (b).

(a)

(b)

Figure 5. a) Broken specimen due to preexisting defects, b) acceptable broken specimens after test

3. RESULTS

As mentioned in section 2, the basic method of presenting engineering fatigue data is by means of the S-N diagram which is a plot of stress S against the number of cycles to failure N. A log scale is usually used for N. The S-N diagrams of Natanz gabbro, Green onyx and Asmari limestone are shown respectively in Figure 6, Figure 7 and Figure 8. Triangle symbols in both aforementioned Figures show the test results of specimens which did not experience failure. Since metal caps were used at the end of the specimens, there is a stress concentration in this location. So the stress amplitude in S-N diagrams are normalized by the obtained ultimate tension strength under bending.

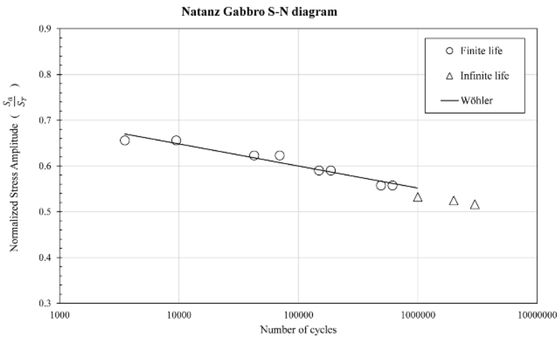

Figure 6. S-N diagram of Natanz gabbro

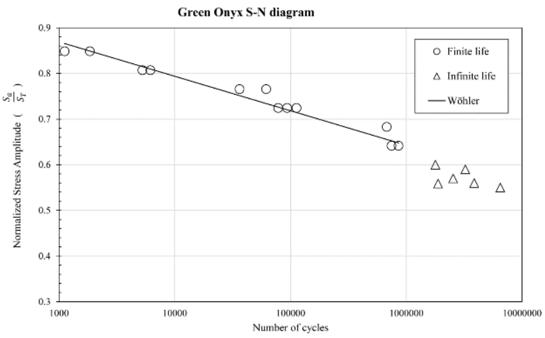

Figure 7. S-N diagram of Green onyx

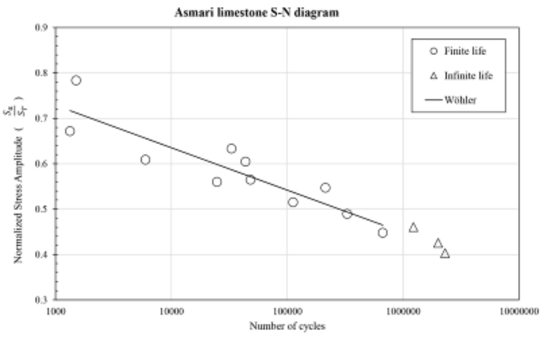

Figure 8. S-N diagram of Asmari limestone

As can be seen in figures 6, 7 and 8, in all types of rocks the number of cycles that a specimen can endure before failure increases with decreasing stress level. When a sample could resist against failure in cyclic loadings beyond 10^6, its fatigue life becomes endless. The stress level that separate specimens with finite and infinite life is known as endurance limit. The results show that endurance limits for Natanz gabbro, Green onyx and Asmari limestone are 14.7MPa (0.53 of its tensile strength), 10.8Mpa (0.6 of its tensile strength) and 10.5MPa (0.46 of its tensile strength) respectively. The results illustrated that the endurance limits for all types of tested rocks in this study is ranged between 0.4 and 0.6 of their tensile strengths that it is in agreement with presented result for fatigue of other materials [2-5; 36; 40-42]. The endurance limit to tensile strength fraction of crystalline rocks was approximated in a higher value compared to the Asmari limestone with non-crystalline micro-structure. It is reported that rock fatigue produces intergranular cracks around grain boundaries by breaking the bonds between the grains and the rock matrix because there is an effective sliding and shear mechanism between grains and rock matrix during each cycle [43]. This process can occur easier in large-grained, multi mineral and altered rock such as Natanz gabbro than fined-grained, dense and uniform rock such as Green onyx. In other word, in a crystalline rock consists of different mineral composition, weak minerals (such as altered mineral of Natanz gabbro to chlorite) control the overall fatigue behavior. So, Natanz gabbro shows lower endurance limit to tensile strength fraction than green onyx. In addition, the test results highlighted a trend in the variation of stress amplitude versus loading cycle number (S-N diagram) which is known as Wöhler relation in the other materials such as metals [44]. Details of Wöhler relation for Natanz gabbro, Green onyx and Asmari limestone are presented in Table 2.

Table 2. Details of Wöhler relation for Natanz gabbro and Green onyx

Rock type	Wöhler relation	The correlation coefficient (R^2)
Natanz gabbro	$\frac{S}{S_T} = 0.8409 - 0.0482 \log N$	0.9412
Green onyx	$\frac{S}{S_T} = 1.0956 - 0.0755 \log N$	0.9435
Asmari limestone	$\frac{S}{S_T} = 1.0088 - 0.0934 \log N$	0.8127

This relation can be written in the general form as follows,

$$\frac{S_a}{S_T} = A - \beta \log N \qquad N \rangle 1000 \tag{6}$$

where S_a is stress amplitude, S_T is tension strength, N is the number of cycles to failure and A is constant value and the parameter " $b = \frac{1}{\beta}$ " is referred to the index of the fatigue curve [44]. The highest values of " β " indicate that the fatigue strength decreased rapidly when the number of cycles is increased. The presented results in Table 2 show that Natanz gabbro show the lowest " β " value and it can be concluded that the resistance of Natanz gabbro against fatigue failure is more than calcic rocks. In addition, crystalline rocks (especially fine grain crystalline rocks) are more fit with Wöhler relation.

4. CONCLUSIONS

The effect of microstructure and mineral composition of different rocks on fatigue behavior under completely reversed loading condition were evaluated. A new fatigue testing machine was developed and stress-life curves and existence of endurance limit were evaluated. After performing the fatigue tests under completely reversed loading condition on two crystalline rocks (Natanz gabbro and Green onyx) and one non-crystalline rock (Asmari limestone) following results associated with fatigue strength of rock samples can be concluded,

- Although, this is the first time that this kind of fatigue tests carried out on rock samples, the obtained results and diagrams are in agreement with presented result for fatigue of other materials. So the proposed method is applicable for estimating the fatigue life of rocks.

- The obtained results for all types of rocks follow Wöhler relation but crystalline rocks (especially fine-grained crystalline rocks) matched better with Wöhler relation.

- Natanz gabbro have the highest "b" (index of fatigue curve) and it can be concluded that resistance of Natanz gabbro against fatigue failure is higher than calcic rocks.

- Variation of endurance limit for Natanz gabbro, Green onyx and Asmari limestone were ranged of 14.7MPa (0.53 of its tensile strength), 10.8Mpa (0.6 of its tensile strength) and 10.5MPa (0.46 of its tensile strength), respectively. The endurance limit to tensile strength fraction of crystalline rocks was approximated in a higher value compared to the Asmari limestone with non-crystalline micro-structure.

- In a crystalline rock consists of different mineral compositions, weak minerals control the overall fatigue behavior.

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