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Research article

Experimental and numerical study of the effect of fatigue on the strength and deformation behavior of granite rock

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Abstract

Fatigue in rocks is a time-dependent failure mechanism caused by repeated cyclic loading, which leads to progressive microcracking, reduction in strength, and eventual sudden failure at stress levels lower than those under static loading. This problem is of critical importance in engineering applications such as mining, tunneling, dam foundations, and underground energy storage, where rock masses are frequently subjected to seismic vibrations, blasting shocks, or machine-induced dynamic loads. Despite its significance, predicting rock fatigue remains challenging due to the heterogeneous nature of rock, experimental limitations, and the lack of universally validated models. In this research, the fatigue behavior of granite rock was investigated through a combined experimental–numerical approach. Laboratory cyclic uniaxial compression tests were performed to evaluate fatigue life, followed by numerical simulations using the Finite Difference Method (FDM) with FLAC3D code and the Finite Element Method (FEM) with ABAQUS software. The models were developed under assumptions of homogeneity, isotropy, and intact rock behavior. Sensitivity analyses were conducted to study the effects of loading cycles, confining pressure, and sample scale. The novelty of this study lies in the comparative evaluation of FDM and FEM approaches for predicting rock fatigue, the integration of laboratory data with numerical modeling for validation, and the systematic analysis of multiple influencing factors (loading cycles, lateral stress, and scale). Results showed that cyclic loading significantly reduces rock strength and elastic modulus compared to static conditions. For example, fatigue life decreased with higher cycle numbers, while confining pressure increased strength and delayed failure. Larger specimens also exhibited longer fatigue life due to stress redistribution. This research contributes to a deeper understanding of fatigue in brittle rocks and provides practical insights for the safe design of rock engineering structures under dynamic conditions. Future improvements could focus on incorporating discontinuities, anisotropy, and particle-scale modeling to better capture the complex mechanisms of fatigue in natural rock masses.

1. INTRODUCTION

Engineering rock structures such as roads, benches, and slopes in surface mines; shafts, tunnels, raises, pillars, and stopes in underground mines; foundations, bridges, dams, and urban railway tunnels in civil engineering; caverns, hydroelectric power plants, nuclear facilities, and nuclear waste disposal sites in energy engineering; and reservoirs and extraction wells in oil and gas engineering are subjected not only to static loading from the weight and gravity of the earth but also typically to dynamic loads from their surroundings [1-2].

Dynamic actions may arise from natural sources such as earthquakes, wind, landslides, and rockbursts, or from anthropogenic sources including vibrations from rotating machinery, blasting operations, or impact forces. Since strength reduction or excessive deformation in these structures is generally unacceptable, the ability to predict rock behavior under both static and dynamic loading conditions is essential for safe design [3-4]. Previous investigations have demonstrated that the mechanical response of rock under dynamic conditions differs from that observed under static loads [5]. In conventional laboratory testing for determining rock properties through stress–strain curves, the applied load is usually monotonic and sustained until failure. This allows sufficient time for complete deformation, and since the sample is loaded only once to failure, the stresses associated with failure appear only once [6]. Thus, such tests essentially reflect the material behavior under constant or static loads. In contrast, dynamic loads are time-dependent and vary in magnitude. The stresses applied to rock in this setting fluctuate between upper and lower bounds, making the evaluation of strength and deformation under dynamic conditions much more complicated [7-9].

Under dynamic loading, rocks are subjected to stress states that are alternating, cyclic, repetitive, or oscillatory [10]. Fatigue in rocks refers to the gradual deterioration of strength and deformation capacity under such repetitive loading [11]. This phenomenon arises when stresses below the ultimate strength of the material are applied repeatedly, leading to microcrack initiation, growth, and eventual failure. As a result, the mechanical response of rock under fatigue loading can differ significantly from its response under static conditions. Given the heterogeneous nature of rock and its inherent uncertainties, fatigue remains a critical yet unpredictable problem that continues to be actively studied [12-13].

Research into rock fatigue has long been a subject of interest within rock engineering, geotechnics, and rock mechanics [14]. However, because rocks are inherently complex and variable, studies in this field are still developing. The concept of fatigue was first introduced for metallic materials in the mid-19th century and later extended to brittle geomaterials such as rock [15-16]. Initial studies on rocks primarily focused on their performance under repetitive loads, especially regarding crack initiation and brittle failure [17-18]. Much of this early work was motivated by the stability of underground openings in mining and tunneling environments subjected to repeated stresses from blasting and heavy equipment. For example, Attewell and Farmer (1973) carried out experiments showing that even cyclic stresses below the ultimate strength could induce crack growth and strength degradation [19]. Studies on crystalline rocks under completely reversed loading have also confirmed the existence of an endurance limit in such materials [20].

From the 1980s onward, efforts were made to develop empirical and theoretical models for predicting rock fatigue life [21]. For instance, Zhenyu and Haihong (1990) [22] and Li et al. (1992) [23] introduced predictive models addressing fatigue behavior and crack propagation in rocks subjected to cyclic loading. Subsequent research confirmed that fatigue characteristics are strongly affected by loading conditions [24]. Bagde and Petroš (2005), for example, examined the role of frequency and amplitude of loading on fatigue performance. In parallel, studies simulating seismic effects helped to deepen understanding of fatigue in rocks under alternating stresses [25].

With advances in laboratory technology since 2000, especially high-precision cyclic testing equipment, more detailed investigations have become possible. For example, Liu and He (2012) [9] and Li et al. (2003) [26] conducted experiments on sedimentary rocks, demonstrating that mineralogy and internal structure play decisive roles in fatigue response. Micro-structural features significantly affect fatigue behavior of intact rocks under cyclic loading [27]. In particular, grain size has been shown to influence rock behavior under cyclic loading conditions [28]. Similar work on different rock types has consistently shown that cyclic loading can cause rocks to fail suddenly at stresses below their static strength [29-36]. In practice, this degradation reduces the stability of rock masses, often leading to structural instability and collapse with serious human and economic consequences. Thus, understanding the fatigue process and its impact on mechanical properties is of major importance.

In recent decades, numerical methods have been increasingly used to investigate rock fatigue behavior due to the inherent challenges in experimental testing of cyclic and time-dependent loading. Methods such as the Finite Element Method (FEM) [37] and the Finite Difference Method (FDM) [38] allow the simulation of rock response under repetitive loading conditions. These tools can estimate stresses, strains, and localized deformations at different scales and can be calibrated with laboratory data. Moreover, numerical modeling enables the construction of S–N curves (stress vs. number of cycles) for rocks, which facilitates the prediction of fatigue life under varied loading conditions [39].

Recent studies have further highlighted the importance of fatigue behavior in geomaterials through both experimental and numerical approaches. Alizadeh et al. (2022) proposed a modified indirect boundary element method based on linear elastic fracture mechanics to assess the fatigue behavior of rock-like materials, providing a robust framework for predicting fatigue crack growth [40]. Building on this, Alizadeh et al. (2023) numerically simulated fatigue crack propagation in heterogeneous geomaterials using the displacement discontinuity method under varied load conditions, emphasizing the critical role of material heterogeneity in crack growth mechanisms [41]. More recently, Dalirnasab et al. (2024) investigated the influence of porosity on the strength and mechanical response of porous geo-materials under cyclic loading, showing that microstructural heterogeneity significantly alters fatigue life and deformation characteristics [42]. Further studies on geo-materials have reinforced the significant role of porosity in altering fatigue life and deformation characteristics [43]. These studies collectively underline the necessity of combining experimental investigations with advanced numerical simulations, as carried out in the present work, to capture both the macroscopic mechanical response and the underlying crack evolution processes.

Despite progress, rock engineering designs often focus primarily on rock behavior under static and uniform loads, with less attention given to variable or cyclic dynamic loading. Yet, since it has been established that dynamic loads may alter rock behavior significantly—making some materials more ductile and others more brittle—investigations into these effects have gained momentum [44-46]. Still, available data remain insufficient, and predictive models often fall short in addressing real-world design needs. Hence, fatigue prediction models are not yet robust or universally reliable, necessitating further comprehensive research.

This study aims to investigate the strength and deformation response of granite rock under cyclic loading conditions. Laboratory uniaxial fatigue tests were conducted using alternating static–dynamic compression. Numerical simulations were then performed using both FDM and FEM to replicate these tests and to analyze fatigue behavior under controlled assumptions of homogeneity and isotropy. A sensitivity analysis was also carried out to examine the effects of loading cycles, confining pressure, and specimen scale on fatigue performance. Novelty and contribution of this research: Unlike many previous studies that focus either on experimental or numerical investigations, this research provides a combined experimental–numerical framework validated on granite. Furthermore, by systematically analyzing multiple influencing parameters (cycles, lateral stress, and scale effect) using both FDM and FEM approaches, this study offers new insights into fatigue mechanisms in brittle rocks. The outcomes contribute to improving fatigue prediction in rock mechanics and guide safer design of rock engineering structures exposed to cyclic and dynamic loads.

2. RESEARCH METHODOLOGY

2.1. Cyclic Uniaxial Compression Test

The Cyclic Uniaxial Compression Test is a widely used laboratory method in rock mechanics, geotechnical engineering, and materials science to investigate the mechanical behavior of brittle materials, such as rocks, under repeated (cyclic) compressive loading. This test is particularly important for studying rock fatigue, which refers to the reduction in strength and changes in mechanical properties due to cyclic loading. The primary goal of the cyclic uniaxial compression test is to evaluate the behavior of rocks under repeated compressive loads, which are common in engineering applications. Determining fatigue life by assessing the number of loading cycles until failure (fatigue life) and constructing S-N (stress-number of cycles) curves is the main objective of this test. In this test, a rock sample is subjected to cyclic compressive loading in a uniaxial (no lateral confinement) setup. Unlike the standard uniaxial compression test, where load is applied monotonically until failure, cyclic loading involves repeated loading and unloading to simulate fatigue behavior. The load oscillates between a minimum and maximum stress, typically below the uniaxial compressive strength (UCS) of the rock.

In this research, a cylindrical granite rock sample with a diameter of 50 mm was first prepared using a core drilling machine. Subsequently, the top and bottom ends of the core sample were cut and polished to ensure flatness and avoid stress concentrations using a cutting machine, resulting in a cylindrical sample with a length of 100 mm (Figure 1). Rock samples are prepared according to the International Society for Rock Mechanics (ISRM) standard.

Fig. 1. **A cylindrical rock sample according to the ISRM standard**

A servo-controlled compression machine is used for cyclic compressive loading in a uniaxial setup in this research. In the first stage, the rock sample was subjected to simple uniaxial compression (static) without cyclic loading until it reached the failure stage. At the end of this stage, the ultimate strength of the rock sample was determined. The mechanical properties of the rock sample are presented in Table 1.

Table 1. Mechanical properties of the rock samples

Parameter	Unit	Value
Density	kg/m³	2700
Modulus of elasticity	GPa	68
Uniaxial compressive strength (UCS)	MPa	110
Cohesion	MPa	53
Friction angle	°	30

In the subsequent stage, the rock sample was subjected to uniaxial compression with cyclic loading (dynamic). In this case, the stress was measured over time at each stage until the sample ultimately reached the failure stage. The stress-time curve obtained is presented in Figure 2. Although this test is very time-consuming with high cycle counts, it accurately simulates real-world cyclic loading conditions. In standard fatigue tests, cyclic loading is usually applied in a sinusoidal waveform to represent realistic variations of stress with time. However, in this study, due to the limitations of the available servo-controlled compression machine, the cyclic load was applied in a stepwise alternating manner rather than in a perfectly sinusoidal form. Despite this difference, the imposed loading–unloading cycles successfully simulated the fatigue process in the rock sample, as they repeatedly subjected the specimen to stresses below its ultimate strength, thereby inducing the formation and propagation of microcracks. Therefore, although the waveform was not strictly sinusoidal, it was sufficient to capture the essential fatigue behavior of the rock under cyclic uniaxial compression.

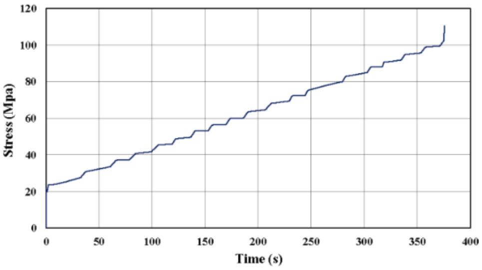


Fig. 2. **Stress-time curve of the rock sample under cyclic uniaxial compression. Note: Although the waveform applied in the test was stepwise rather than perfectly sinusoidal (due to equipment limitations), it effectively simulated alternating cyclic loading conditions for fatigue analysis.**

2.2. Numerical Modeling Of The Fatigue Testing

The cyclic uniaxial compression test provides valuable experimental data for calibrating numerical models. In this research, two numerical methods, finite difference and finite element, have been used to model the fatigue test of seamless rock.

In this study, two types of loading were considered. In FLAC3D, constant-amplitude cyclic loading was applied to directly represent classical fatigue testing conditions. In contrast, in ABAQUS, time-varying dynamic loading was used to simulate realistic engineering conditions such as seismic or blasting loads. While the latter is not a pure cyclic load, the repetitive stress history induces progressive stiffness degradation and strength reduction, consistent with fatigue behavior. This dual approach provides a broader understanding of how different loading styles contribute to fatigue mechanisms in rock.

Following a phenomenological macro-scale strategy, cyclic loading was imposed on an intact continuum, and the degradation of stiffness/strength parameters with cycles was calibrated using laboratory data. The model does not resolve microcrack initiation and growth; instead, it reproduces the observed macroscopic fatigue trends.

2.2.1. Finite Difference Modeling

The finite difference method (FDM) is a widely used numerical technique for solving differential equations, applied in rock mechanics and continuum mechanics to analyze the mechanical behavior of materials. FDM approximates the derivatives in differential equations using finite differences on a discrete grid. In this method, the problem domain, like a rock sample, is divided into a regular grid of points. Then, governing equations are solved approximately at each grid point. Finally, stresses, strains, and displacements are calculated at each node and propagated to neighboring nodes to simulate the overall system behavior.

In this research, the FDM is employed for studying rock fatigue due to its ability to handle dynamic and nonlinear problems by using FLAC software to simulate cyclic loading on the rock sample. FLAC (Fast Lagrangian Analysis of Continua) is a powerful numerical modeling tool based on the finite difference method, which is widely used in modeling the behavior of rock under cyclic or repetitive loading. Due to its ability to simulate nonlinear behavior, large deformations, and complex rock-structure interactions, FLAC3D is selected for studying rock fatigue.

FLAC3D version 5.0 was used in this research to model the fatigue test on the rock sample. The first step in modeling with the aforementioned software is the creation of the model geometry. Accordingly, based on the dimensions of the rock sample subjected to uniaxial compressive testing, a cylindrical rock sample with a diameter and height of 5 cm and 10 cm, respectively, was constructed as the model geometry (Figure 3). In the next step, the model was meshed with radial meshing for the cylindrical model. The mesh density was chosen after preliminary mesh sensitivity checks. These tests indicated that further mesh refinement produced only minor numerical variations but did not affect the overall fatigue trends, such as strength degradation with cycles, the influence of confining pressure, and the scale effect. Since the purpose of this study was to capture the general fatigue mechanisms and comparative behaviors rather than exact numerical values, the adopted mesh density was considered sufficient. Nonetheless, we acknowledge that a finer mesh would increase numerical precision, and this is recognized as a limitation of the present study. Future work will incorporate more refined meshes to further validate the findings.

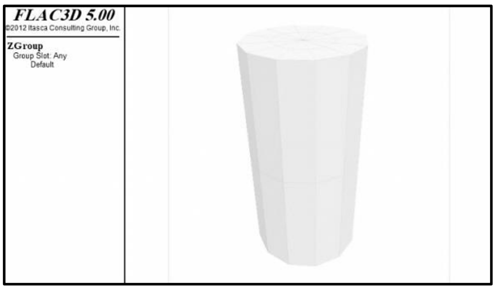


Fig. 3. Model geometry for fatigue modeling in FLAC3D.

In the next stage, the mechanical properties of the tested rock (Table 1) were assigned to the model using the Mohr-Coulomb failure criterion. Subsequently, boundary conditions were applied to the model in accordance with the conditions of the uniaxial compressive test on the rock sample. To simulate cyclic-alternating loading in the uniaxial compressive test, loading was applied to the model by imposing vertical velocity on the top and bottom surfaces (Figure 4). In this stage, a negative velocity (opposite to the vertical axis direction) was applied to the top surface of the model, and a positive velocity was applied to the bottom surface. In this case, the velocity magnitude on both surfaces was set to a very low value (0.0001 mm/s). Additionally, similar to the uniaxial compressive test, the lateral (confining) load applied to the sample's sidewalls was set to zero.

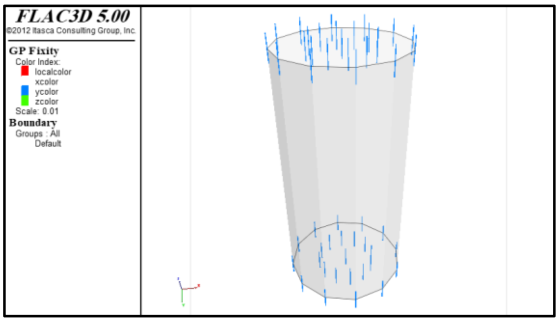


Fig. 4. Loading applied to the model under cyclic uniaxial compression.

With the application of boundary conditions and repetitive loading, the model was executed until it reached the desired compressive strength under alternating loading. In dynamic loading, the load is applied over extended periods, and its intensity continuously varies. Nevertheless, in cyclic uniaxial compressive testing, similar to static loading, the stress-strain curve obtained is typically used to determine the uniaxial compressive strength (corresponding to the peak point of the curve). In this research, through modeling and cyclic loading, the uniaxial compressive strength of the rock was determined to be approximately 25 MPa. Based on this value, in the cyclic loading conducted to investigate the model's fatigue behavior, the model's strength was obtained for every 100 loading cycles. For example, after running the model, the uniaxial compressive strength of the model after 1,000,000 loading cycles was reduced to approximately 50% of the rock's uniaxial compressive strength, i.e., 12 MPa. Ultimately, using these values and cycles, the S-N curve (stress or strength versus number of loading cycles) was obtained (Figure 5). In these curves, the letter S represents the failure stress (vertical axis), and the letter N indicates the number of loading cycles required for failure to occur (horizontal axis). According to this curve, if repetitive loads below the fatigue limit are applied, no failure will occur within the material.

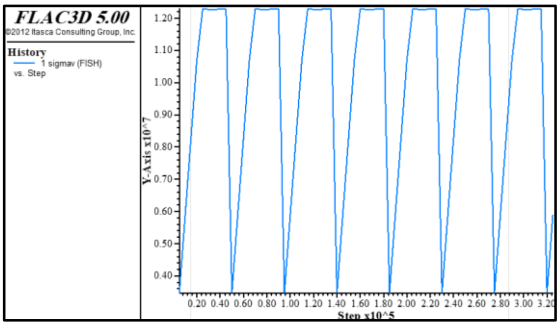


Fig. 5. Stress-load (S-N) curve at the end of the fatigue test modeling.

The comparison of the uniaxial compressive strength results obtained under static loading versus dynamic loading indicates that the load required to cause fatigue-induced failure in the model developed in this study is significantly lower than the static load-bearing capacity of the rock sample. Therefore, it can be concluded that the likelihood of rock failure under dynamic loading conditions is higher compared to static loading conditions. In this case, if dynamic loading is repeated over a large number of cycles, the probability of failure will also increase.

It should be noted that in FLAC3D, the dynamic time increment (Δt) is automatically determined by the CFL stability condition, which depends on the smallest zone size, material density, and elastic wave velocity. In this study, Δt was approximately 10^{-7}–10^{-6} s. Since each calculation step corresponds to one increment of Δt, the results presented versus step number are directly proportional to real dynamic time. Therefore, the plotted results using step count reflect the same trends as if presented against actual time.

2.2.2. Finite Element Modeling

The finite element method (FEM) is also one of the most widely used numerical techniques in rock mechanics and continuum mechanics for analyzing the mechanical behavior of materials. FEM divides the problem domain into smaller elements (finite elements) connected at nodes. Then, stresses, strains, and displacements are computed at element nodes. Governing equations are solved approximately for each element and assembled to simulate the overall system behavior.

In continuation of this research, the FEM is employed for studying rock fatigue due to its ability to model nonlinear behavior by using ABAQUS software to simulate cyclic loading on the rock sample. ABAQUS is a finite element analysis (FEA) software, widely used in rock mechanics, to simulate and analyze material behavior under various conditions, including rock fatigue. It should be noted that ABAQUS offers various solvers that can be used depending on the type of problem. In this study, the explicit solver was employed. This solver is suitable for modeling a wide range of static and dynamic problems, including stress and strain analysis, vibration analysis, impact, blast, and also quasi-static or nonlinear problems where contact conditions change. Also, the force-control method was used to model the fatigue of the rock sample.

Similar to most numerical software, in ABAQUS, modeling begins with creating a new file and constructing the model geometry. Therefore, in the first step, based on the dimensions of the rock sample under uniaxial compression testing, a cylindrical rock sample (3D model) with a diameter of 5 cm and a height of 10 cm was created. In the next step, considering the Mohr-Coulomb failure criterion, the mechanical properties of the rock sample (Table 1) were assigned to the model. In the continuation, considering the cylindrical geometry of the model, radial meshing (native mesh) was used for meshing the model (Figure 6).

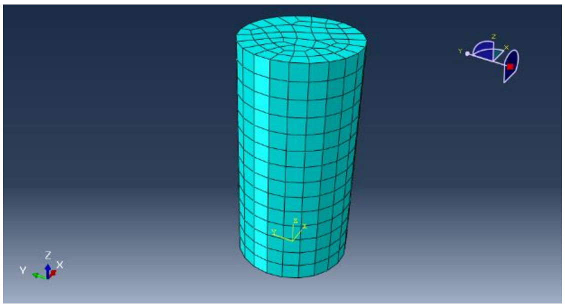


Fig. 6. Geometry and meshing of the model built for fatigue modeling in ABAQUS.

In the next step, to simulate the uniaxial compression test on the rock sample, similar to the modeling approach described in the previous section using FLAC, boundary conditions were applied to the model. Finally, from the job module, the create job option was selected to execute the model. This module is used to process the data. At this stage, the equations are formulated by the software and subsequently solved. Therefore, in this stage (modeling), the software solves the physical model created in the previous stage (pre-processing) and transfers it to the next stage (post-processing).

3. RESULTS AND DISCUSSION

3.1. FDM Modeling

In Figs. 7 and 8, the contour lines of vertical and horizontal normal stresses of the model after applying cyclic loading (at the end of the fatigue test) are shown. As observed in Figure 7, the vertical normal stress increases from the center toward the outer edges of the model. Additionally, in this case, as shown in Figure 8, the horizontal normal stress decreases from the center toward the outer edges of the model. In reality, the increase and decrease of stresses in different directions typically lead to the formation of progressive fractures in the rock sample, and continued loading ultimately results in rock failure.

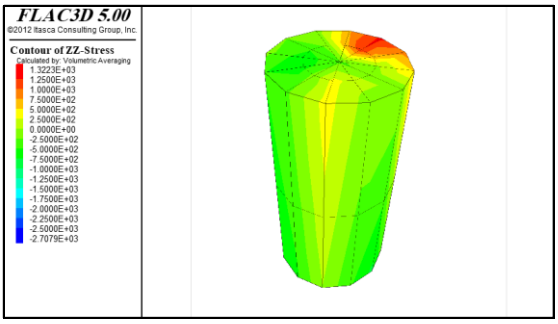


Fig. 7. **Normal stress distribution of the cylindrical model in the vertical direction.**

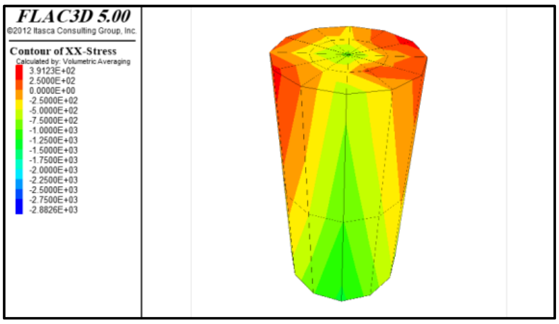


Fig. 8. **Normal stress distribution of the cylindrical model in the horizontal direction.**

Additionally, in Figure 9, the contour lines of the maximum principal stress of the model are shown at the final stage of cyclic loading, i.e., near the end of the fatigue test, when significant damage had already developed in the specimen. Although the specimen geometry and the applied loading conditions were symmetric, the distribution of principal stress in the model appears non-symmetric. This asymmetry arises from the progressive initiation and propagation of microcracks within the rock, which are influenced by local heterogeneities and imperfections in the material. These microstructural variations lead to localized stress concentrations and redistribution, thereby breaking the theoretical symmetry of the stress field under cyclic loading. Consequently, multiple principal stress planes are formed, which act as preferential paths for crack growth and fatigue failure.

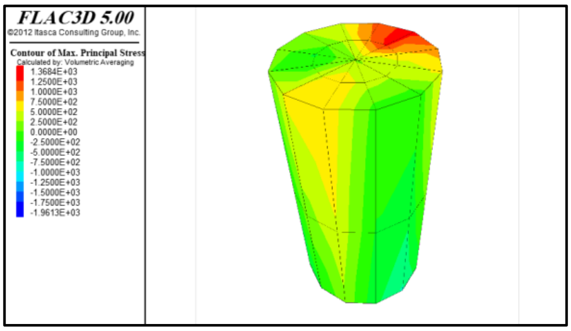


Fig. 9. **Distribution of maximum principal stress in a cylindrical model at the final stage of cyclic loading.**

In Figs. 10 and 11, the contour lines of the model's displacement in the horizontal and vertical directions, respectively, after applying cyclic loading (at the end of the fatigue test), are shown. As observed in Figure 10, the maximum displacement along the x-axis is observed at the model's sidewall (equal to 0.09 mm). Additionally, in this case, as shown in Figure 11, the maximum displacement along the y-axis occurs near the bottom of the model (equal to 0.07 mm). This localized concentration of displacement is mainly related to the boundary conditions applied at the bottom surface, which caused stress redistribution and accumulation of deformation in that region. A comparison of these two figures indicates that the maximum displacement in the horizontal direction is greater than in the vertical direction. In reality, due to the absence of lateral loads in the uniaxial compressive test, the displacement along the x-axis is typically greater. This factor results in higher lateral strain compared to axial strain, consequently increasing Poisson's ratio. Therefore, it can be concluded that the deformation behavior trend of the model under dynamic loading is approximately similar to that under static loading.

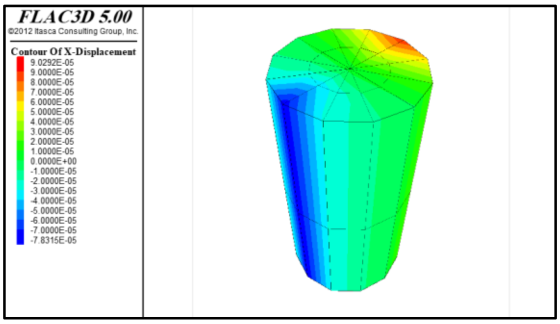


Fig. 10. **Displacement contour of the cylindrical model in the X-axis.**

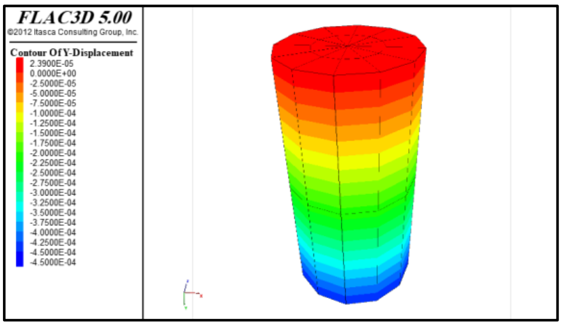


Fig. 11. **Displacement contour of the cylindrical model in the Y-axis.**

It should be noted that at the microscopic scale, displacement is due to the formation and growth of cracks in the material during cyclic loading. Typically, in the initial cycles of fatigue loading, crack growth is very slow and stable. However, as the number of loading cycles increases, crack growth becomes rapid and unstable, ultimately leading to the failure of the sample. Investigating this process in the laboratory is possible using high-magnification digital cameras, a facility that was not available in this study. Additionally, in modeling, software capable of analyzing material behavior at the particle level and microscopic scale should be used. This capability is not available in the FLAC software, but it is present in software based on the Discrete Element Method (DEM), such as PFC.

Nevertheless, in the FLAC software, it is possible to examine the strain rate (deformation relative to time) in the model. In fact, the strain rate reflects the changes in the distance between adjacent parts of the sample near the point under investigation over time. In this regard, the contraction or expansion of the material (volumetric strain rate) and the deformation of the body through progressive shear at constant volume (shear strain rate) are the two components constituting the strain rate. The distribution of the maximum shear strain rate in the model is shown in Figure 12. Typically, if all particles of a body move at the same velocity (in the same direction) or are displaced at the same angle, the strain rate will be zero. Therefore, variations in the shear strain rate in the model indicate the fatigue of the body at the end of the loading process.

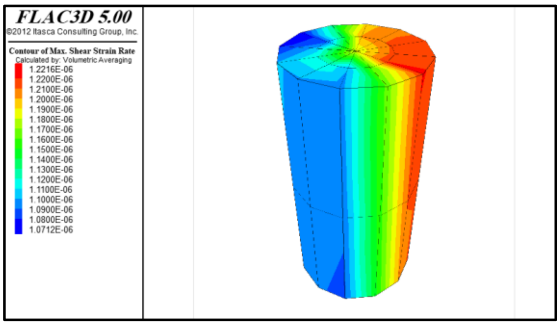


Fig. 12. **Shear strain rate distribution of the cylindrical model.**

Although stress contours illustrate the redistribution of stresses under cyclic loading, they do not directly indicate the initiation and growth of cracks. In FLAC3D, crack propagation is not explicitly modeled; instead, yielded zones can be used to identify regions approaching failure. In this study, our interpretation of progressive shear plane development is based on stress redistribution patterns combined with the identification of zones reaching the yield condition. This approach is limited to macro-scale interpretation of fatigue failure, and future research will incorporate advanced constitutive or discrete methods to more directly capture microcrack growth.

3.1.1. Effect of loading cycles on the fatigue

To investigate the effect of loading cycles on fatigue (maximum sample strength), a sensitivity analysis was conducted. For this purpose, the sample's strength was determined over various loading cycles (Table 2). According to Table 2, the modeled rock sample exhibits a gradual reduction in strength as the number of loading cycles increases. For example, the strength decreases from 58.58 MPa at the first cycle to 34.05 MPa after one million cycles, indicating a nearly 40% reduction. This clearly demonstrates the fatigue effect, where repetitive cyclic stresses progressively weaken the rock. Since loading cycles are directly related to time and loading frequency, applying stresses more frequently within shorter intervals accelerates strain accumulation and reduces the rock’s strength. Therefore, even without a graphical representation, the tabulated values highlight a distinct decreasing trend in strength with increasing cycles.

It should be noted that, in addition to the number of loading cycles, the duration of each cycle and the overall loading time can also influence the fatigue response of rock. Longer cycle periods may allow more microcrack growth and energy dissipation per cycle, whereas higher loading rates (shorter cycle durations) may limit crack propagation but accelerate cumulative damage. In this study, the numerical simulations were performed with time steps automatically determined by the CFL stability condition in FLAC3D, and therefore, the time effect was implicitly included but not systematically varied. This remains a limitation of the current research, and future studies should explicitly examine the influence of cycle duration and loading frequency on rock fatigue behavior.

Table 2. Strength changes versus the number of loading cycles during modeling

Number of loading cycles	Maximum strength of model (MPa)
1	58.58
10	58.14
100	46.89
500	55.59
1000	52.78
5000	51.04
50000	50.26
100000	51.28
200000	48.06
300000	36.72
400000	36.10
500000	40.18
600000	41.12
700000	32.37
800000	39.86
900000	31.63
1000000	34.05

3.1.2. Effect of confining pressure on the fatigue

In nature, rocks are subjected to both horizontal and vertical in-situ stresses. However, in uniaxial compressive tests, only axial (vertical) stresses are applied to the sample. Therefore, to investigate the effect of lateral (horizontal) stresses on fatigue, this section focuses on modeling a triaxial compressive test under lateral loading. For this purpose, fatigue (maximum sample strength) was examined with respect to variations in lateral stress at three levels: 1, 2, and 3 MPa (Table 3). In this table, the relative cycle is calculated by dividing the number of loading cycles by 1,000,000 (the final cycle).

According to Table 3, the strength of the modeled rock sample increases consistently with higher confining pressure at all loading stages. For instance, near the final stage of cyclic loading, the strength rises from 207.25 MPa at 1 MPa confining pressure to 308.59 MPa at 3 MPa confining pressure. This shows a significant strengthening effect of lateral stress, which delays fatigue by suppressing crack initiation and propagation. The tabulated values make this trend explicit by allowing direct numerical comparison between different levels of confining pressure. Conversely, the absence of lateral stresses causes an increase in strain, which promotes the growth of initial cracks. In this case, fatigue and failure occur earlier in the model.

Table 3. Strength changes versus number of confining pressure during modeling

Number of loading cycles (Relative cycle)	Maximum strength of model (MPa)		
	Confining pressure (MPa)		
	1	2	3
1	169.87	219.95	253.70
0.9	173.81	225.28	260.37
0.8	174.24	227.42	260.75
0.7	178.11	231.08	265.47
0.6	181.97	237.04	271.23
0.5	189.59	245.24	283.16
0.4	193.54	250.34	287.32
0.3	195.53	253.17	290.86
0.2	201.43	261.86	302.0
0.1	203.34	263.02	301.57
0	207.25	269.42	308.59

3.1.3. Effect of scale on fatigue

In this section, a sensitivity analysis was conducted to investigate the effect of sample scale on fatigue (maximum sample strength). For this purpose, the strength of three rock sample models (with diameters of 5, 10 and 15 cm) was determined under a constant applied force across different loading cycles (Figure 13). This approach was deliberately adopted to simulate practical engineering conditions, where rock masses of different scales are often subjected to the same external load (e.g., seismic forces, blasting vibrations, or machine-induced dynamic forces) rather than constant stress. As shown in Figure 13, the results indicate that as the specimen diameter increases, the average applied stress decreases due to the larger cross-sectional area. Consequently, the larger samples exhibit greater strength and delayed fatigue. This finding highlights the importance of specimen geometry in fatigue studies and its implications for engineering design under constant external loads.

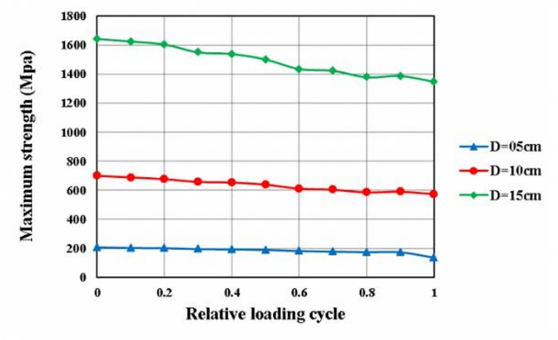


Fig. 13. **Strength distribution with respect to the sample diameter (D).**

In the scale effect analysis, both specimen diameter and height were increased proportionally so that the length-to-diameter ratio (L/D) remained constant in all models. This approach ensures that the observed differences are due to specimen scale rather than variations in aspect ratio (tallness).

3.1.4. Effect of fatigue on the elastic modulus

The elastic modulus (Young's modulus) refers to the amount of stress generated per unit of deformation in a material. In essence, the elastic modulus represents a material's resistance to deformation under the stress induced by applied loading. This parameter is typically used to predict a material's strength to compressive and tensile stresses and is generally derived from the axial stress-strain curve (in the elastic region). Consistent with previous sections, a sensitivity analysis was conducted in this section to investigate the effect of loading cycles during the fatigue process on the elastic modulus. To this end, the elastic modulus values of the model were obtained over various loading cycles (Figure 14). According to this figure, it can be concluded that fatigue has a reducing effect on the elastic modulus, causing a decrease in the elastic modulus of the rock as the number of loading cycles increases. This results in a reduction in the rock's strength and stiffness.

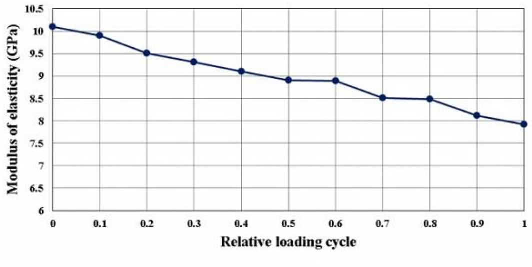


Fig. 14. **Elastic modulus distribution with respect to the number of loading cycles.**

3.2. FEM Modeling

The distribution of vertical displacement in the model (U, magnitude) at the end of the loading and solution stage is shown in Figure 15. As can be observed in this figure, the maximum displacement of 0.1425 units (red regions) occurs at the top or a free surface of the cylinder, indicating significant deformation under cyclic loading. This could be a critical area for fatigue crack initiation. The zero displacement (blue regions) suggests fixed boundaries or supports, which are typical in fatigue tests to simulate real-world constraints.

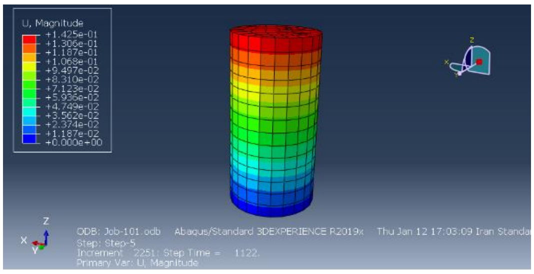


Fig. 15. **Vertical displacement distribution (mm) of the cylindrical model in ABAQUS.**

Additionally, Figure 16 illustrates the contours of the maximum principal stress in the model. According to this figure, the maximum principal stress (strength) developed in the sample after cyclic loading is approximately 106 MPa. Comparing this value with the uniaxial compressive strength of the rock under static loading conditions (laboratory test), which is 110 MPa, indicates that under dynamic loading, the strength decreases by about 4% due to fatigue during the cyclic loading process. Therefore, it is crucial to consider the fatigue of rock over time, or the reduction in strength, in the design of rock structures subjected to dynamic loading.

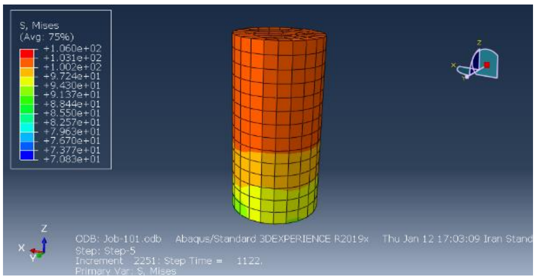
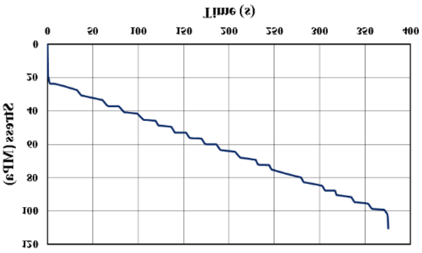
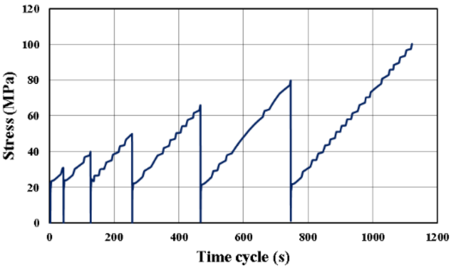


Fig. 16. **Maximum principal stress distribution (MPa) of the cylindrical model in ABAQUS.**

In Figure 17, the stress-time curve is presented for both static and dynamic-cyclic loading conditions. These graphs also indicate that under static loading (Figure 17-a), the rock sample reaches its ultimate strength and failure stage at a stress close to 110 MPa. In contrast, under cyclic loading (Figure 17-b), this value is reduced to approximately 106 MPa. This demonstrates that the type of loading can significantly affect the ultimate strength of the rock. Static loads, or constant forces, are applied continuously to an object, typically in a single direction. These loads do not significantly contribute to material fatigue and generally cause conventional failure in the object. On the other hand, dynamic or cyclic loads are the primary cause of material fatigue. Due to their periodic and alternating nature, these loads gradually initiate and propagate cracks on the rock surface, leading to failure. Consequently, under cyclic loading, the material fails at a stress level lower than its allowable limit.



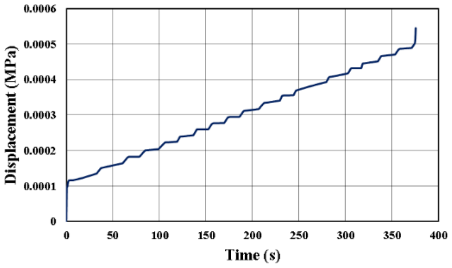
(a)



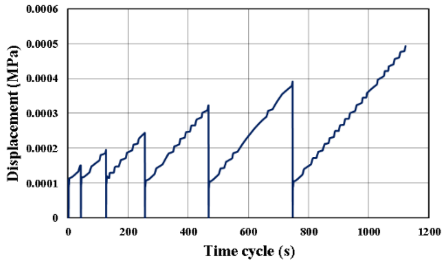
(b)

Fig. 17. Stress-time curve of the model under a) static loading, b) dynamic-cyclic loading condition.

In Figure 18, the displacement-time curve is presented for both static and dynamic-cyclic loading conditions. By comparing these graphs, it can be concluded that under static loading (Figure 18-a), the displacement increases incrementally over time until the rock reaches its yield point. However, under cyclic loading (Figure 18-b), the displacement changes are not stepwise but occur in an alternating manner. In this case, the model reaches its yield point with less displacement compared to the static loading condition. This indicates that the pattern of displacement changes over the lifespan of a rock structure significantly affects its deformation behavior. Specifically, with less displacement, the likelihood of structural failure under dynamic loading is higher compared to static loading conditions. Therefore, if the dynamic loading process is repeated over a large number of cycles, the accumulated displacement will induce fatigue in the material sooner (resulting in a shorter fatigue life) and increase the probability of failure. Since the lifespan of rock structures is dependent on the fatigue life of the rock, efforts should be made to construct engineering structures in rocks with higher fatigue life.



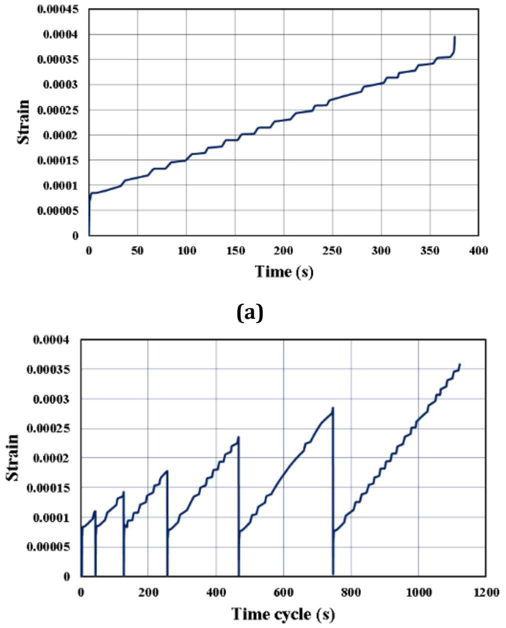
(a)



(b)

Fig. 18. Displacement-time curve of the model under a) static loading, b) dynamic-cyclic loading condition.

Similar to displacement, Figure 19 presents the strain-time graph for both static and dynamic-cyclic loading conditions. Strain, being a dimensionless parameter, indicates the extent of deformation in the material over the duration of loading. By comparing these graphs, it can be concluded that under static loading (Figure 19-a), the rock sample reaches its ultimate strength at a higher strain compared to the cyclic loading condition (Figure 19-b). In static loading, due to the gradual application of force, there is sufficient time for strain to develop within the material. However, in dynamic loading, the loading and unloading of the material occur alternately. Consequently, after each unloading cycle, a significant amount of residual strain remains in the material. This leads to a reduction in the material's strength in subsequent loading cycles. Therefore, in cyclic loading, as the loading and unloading process continues, more residual strains accumulate in the material. Ultimately, the material completely loses its strength and fails under the maximum applied load. This phenomenon illustrates the fatigue of the material due to the application of cyclic loads and the accumulation of residual strains.



(a)

(b)

Fig. 19. **Strain-time curve of the model under a) static loading, b) dynamic-cyclic loading condition.**

In addition to the differences in displacement and strain under static and cyclic loading, the slope of the stress–strain curves was also observed to change progressively during cyclic loading. At the beginning of the fatigue process, the slope increases gradually, reflecting a temporary hardening behavior. However, as the number of cycles increases, the slope rises more steeply and approaches a near-vertical trend at the final stage of loading. This indicates that the material loses its ability to accommodate further strain, and sudden fatigue failure occurs. Such an evolution of the stress–strain curve provides an important indicator of fatigue progression in the rock sample.

3.2.1. Effect of loading cycles on the fatigue

Similar to the previous section (3.1.1), in this section, using the model developed in ABAQUS, a sensitivity analysis of the loading cycle on fatigue (maximum strength of the sample) was conducted. To this end, the ultimate strength of the sample was determined over five loading cycles (Table 4). According to this table, as the number of loading cycles increases, the strength of the modeled rock sample decreases. Based on this, after five loading cycles, the sample's strength reaches approximately 90% of its uniaxial compressive strength, which is 100.289 MPa.

Table 4. Strength changes versus the number of loading cycles during modeling

Number of loading cycles	Maximum strength of model (MPa)
1	110.603
2	108.912
3	105.565
4	103.457
5	100.289

3.2.2. Effect of confining pressure on the fatigue

In this section, similar to the previous section (3.1.2), to investigate the effect of lateral (horizontal) stresses on fatigue, a triaxial compression test under lateral loading was modeled in ABAQUS. For this purpose, three levels of lateral stress—10, 50, and 100 MPa—were applied to the model. The cyclic stress-strain curves obtained for each case are shown in Figure 20. As evident from the figure, these curves exhibit a hysteresis pattern. A hysteresis curve is essentially a stress-strain curve, with the difference that instead of uniform loading, the loading is applied cyclically (in a loading-unloading manner). These curves allow for the examination of the real and nonlinear behavior of materials under cyclic loading. In the cyclic loading performed, the strength initially increases due to hardening behavior, but ultimately, the stiffness (slope of the curve) and strength decrease due to softening behavior. As shown in Figure 20, the cyclic stress–strain responses form hysteresis loops (highlighted in red), which represent the energy dissipated during each loading–unloading cycle. The increasing area of these red loops indicates progressive damage accumulation and reduction in stiffness as the number of cycles increases. This behavior demonstrates the gradual transition of the rock from hardening to softening under cyclic loading.

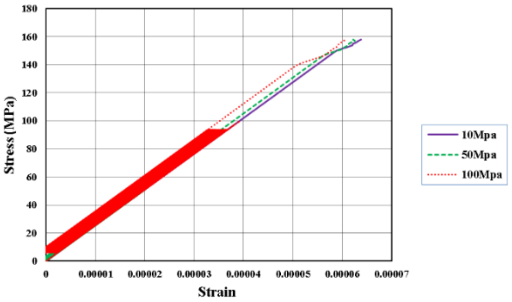


Fig. 20. **Cyclic stress-strain curve of the model under confining pressure.**

3.2.3. Effect of scale on fatigue

Similar to the previous section (3.1.3), in this section, a sensitivity analysis was conducted using ABAQUS to investigate the effect of sample size on fatigue (maximum strength of the sample). According to Figure 21, the results show that increasing the sample diameter under the condition of a constant applied force leads to higher overall strength and delayed fatigue onset. Similar to the FDM analysis, this modeling strategy was intentionally selected to reflect realistic field scenarios in which structures of different sizes may experience the same external loading rather than equalized stress conditions. The decrease in nominal stress with increasing specimen size redistributes the applied load, allowing larger samples to better withstand cyclic loading. This demonstrates that scale plays a significant role in fatigue life when external forces are constant, which is directly relevant to many engineering applications.

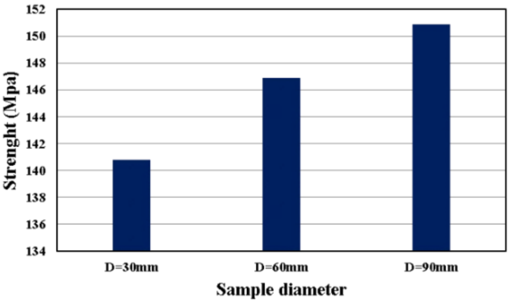


Fig. 21. Strength distribution with respect to the sample diameter (D).

3.2.4. Effect of fatigue on the elastic modulus

In this section, similar to the previous section (3.1.4), the effect of loading cycles during the fatigue process on the elastic modulus was investigated using ABAQUS. To this end, the values of the elastic modulus of the model were obtained over the loading cycles (Figure 22). According to this figure, it can be concluded that fatigue has a reducing effect on the elastic modulus, leading to a decrease in the rock's elastic modulus during the loading cycles.

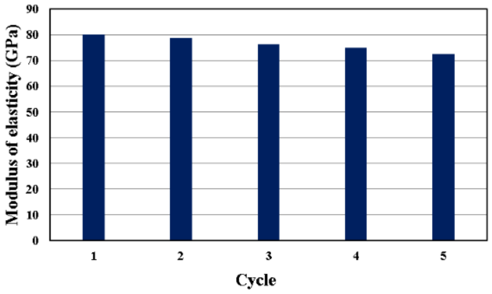


Fig. 22. Elastic modulus distribution with respect to the number of loading cycles.

4. CONCLUSION

The primary objective of this study was to investigate the strength and deformation behavior of rock during the fatigue process. To this end, using numerical modeling through FLAC3D finite difference code and ABAQUS finite element software, a fatigue test was simulated on an intact rock sample without discontinuities. The models developed in this experiment, similar to the uniaxial compression test, were subjected to alternating static-dynamic cyclic loading, and fatigue was determined. Additionally, at the end of each section, a sensitivity analysis was conducted to examine the effects of factors such as loading cycles, confining pressure, and sample size on fatigue in each condition. Some of the important results of this research are as follows:

1) Finite element method superiority: The finite element method (FEM), as used in ABAQUS, generally offers greater capability and higher accuracy than the finite difference method (FDM) for predicting fatigue in rock under cyclic loading, due to its ability to model complex geometries and material behaviors.

2) Low cyclic loads: If cyclic loads are applied below the fatigue limit of the rock, fatigue failure will not occur, as the material can endure these stresses without cumulative damage.

Dynamic vs. static loading: Cyclic dynamic loading increases the likelihood of fatigue failure in rock compared to static loading, as it introduces repeated stress cycles that exacerbate micro-damage.

3) Effect of loading cycles: As the number of dynamic loading cycles increases, the displacement and probability of fatigue failure in the rock rise, while its fatigue life decreases, as observed in the high displacement (0.1425 units) in the model after 112.2 time steps.

4) Progressive cracks: In cyclic loading, the variation in stress levels causes the formation and growth of progressive cracks in the rock, ultimately leading to fatigue failure, which may be reflected in the high-displacement regions of the model.

5) Residual strain: Cyclic loading and unloading induce residual strain in the rock, contributing to fatigue failure by accumulating permanent deformation over time.

6) Asymmetric Stress Distribution: In cyclic loading, the asymmetric distribution of principal stresses (as noted in the model) creates multiple principal stress planes. These planes serve as sites for crack initiation and propagation, driving fatigue in the rock.

7) Shear Strain Rate Changes: Variations in the shear strain rate during cyclic loading indicate fatigue, suggesting that the rock's internal structure is undergoing damage, which could correlate with the observed displacement gradients.

8) Stress–Strain Curve Evolution: The slope of the stress–strain fatigue curves evolves progressively during cyclic loading. At early stages, a gradual increase in slope reflects temporary hardening behavior, while at the final cycle, the slope approaches a near-vertical trend. This behavior indicates the onset of sudden fatigue failure, consistent with the extreme deformation observed in the model.

9) Cycle Impact on Fatigue Life: An increase in loading cycles reduces the fatigue life of the rock, consistent with the progressive damage implied by the displacement results.

10) Lateral Stress Effects: Applying and increasing lateral stresses enhances the rock's fatigue life. Higher lateral loads increase the hardening factor (stress-strain curve slope), indicating greater hardening behavior, which is associated with longer fatigue life in rocks with such properties.

11) Scale Dependency: Fatigue is scale-dependent; larger rock specimens tend to exhibit longer fatigue life due to a lower probability of critical flaw concentration, affecting how displacement and stress are distributed in the model.

12) Reduced Strength Parameters: Fatigue reduces the rock's strength parameters, such as its elastic modulus, which may be inferred from the significant deformations observed after prolonged cyclic loading.

13) Although the present study provides new insights into fatigue mechanisms, the results are specifically valid for granite rock. Extending these findings to other rock types requires further experimental and numerical investigations, as differences in mineralogy, texture, and microstructure may significantly influence fatigue behavior.

The cyclic uniaxial compression test is a critical tool for studying rock fatigue under repeated compressive loads. It provides essential data for designing safe rock structures and predicting fatigue life. By combining test results with numerical models, engineers can simulate and predict rock behavior in complex scenarios.

This study focuses on macro-scale fatigue behavior; microcrack evolution is not modeled explicitly. Future work will employ damage-based or fracture-enabled formulations (e.g., CDM, CZM/XFEM, UMAT/VUMAT, or DEM) to capture crack initiation and propagation.

REFERENCES

[1] Gong, F., Zuo, J., Zhang, X., & Liu, R. (2021). Deep Rock Behaviour in Engineering Environments. Advances in Civil Engineering, 2021.

[2] Wang, Z., Huang, J., Chen, Y., Li, X., Liu, T., & Meng, F. (2023). Dynamic mechanical properties of different types of rocks under impact loading. Scientific Reports, 13(1), 19147.

[3] Zhou, Z., Cai, X., Li, X., Cao, W., & Du, X. (2020). Dynamic response and energy evolution of sandstone under coupled static–dynamic compression: insights from experimental study into deep rock engineering applications. Rock mechanics and rock engineering, 53, 1305-1331.

[4] Zhao, G., Zhang, L., Dai, B., Liu, Y., Zhang, Z., & Luo, X. (2022). Experimental Investigation of Pre-Flawed Rocks under Dynamic Loading: Insights from Fracturing Characteristics and Energy Evolution. Materials, 15(24), 8920.

[5] Liu, Y., & Dai, F. (2021). A review of experimental and theoretical research on the deformation and failure behavior of rocks subjected to cyclic loading. Journal of Rock Mechanics and Geotechnical Engineering, 13(5), 1203-1230.

[6] Noorian-Bidgoli, M. (2014). Strength and deformability of fractured rocks. PhD Thesis, KTH Royal Institute of Technology, Stockholm, Sweden.

[7] Li, N., Chen, W., Zhang, P., & Swoboda, G. (2001). The mechanical properties and a fatigue-damage model for jointed rock masses subjected to dynamic cyclical loading. International Journal of Rock Mechanics and Mining Sciences, 38(7), 1071-1079.

[8] Bagde, M. N., & Petroš, V. (2005). Fatigue properties of intact sandstone samples subjected to dynamic uniaxial cyclical loading. International Journal of Rock Mechanics and Mining Sciences, 42(2), 237-250.

[9] Liu, E., & He, S. (2012). Effects of cyclic dynamic loading on the mechanical properties of intact rock samples under confining pressure conditions. Engineering Geology, 125, 81-91.

[10] Song, H., Zhang, H., Fu, D., & Zhang, Q. (2016). Experimental analysis and characterization of damage evolution in rock under cyclic loading. International Journal of Rock Mechanics and Mining Sciences, 88, 157-164.

[11] Kang, P., Jiaqi, Z., Quanle, Z., & Junhui, M. (2022). Fatigue deformation characteristics and damage model of sandstones subjected to cyclic loading: Implications for fatigue life prediction. International Journal of Geomechanics, 22(1), 04021261.

[12] Cerfontaine, B., & Collin, F. (2018). Cyclic and fatigue behaviour of rock materials: review, interpretation and research perspectives. Rock mechanics and rock engineering, 51(2), 391-414.

[13] Wang, J., Li, J., Shi, Z., & Chen, J. (2022). Fatigue damage and fracture evolution characteristics of sandstone under multistage intermittent cyclic loading. Theoretical and Applied Fracture Mechanics, 119, 103375.

[14] Burdine, N. T. (1963). Rock failure under dynamic loading conditions. Society of Petroleum Engineers Journal, 3(01), 1-8.

[15] Schütz, W. (1996). A history of fatigue. Engineering fracture mechanics, 54(2), 263-300.

[16] Bathias. (1999). There is no infinite fatigue life in metallic materials. Fatigue & fracture of engineering materials & structures, 22(7), 559-565.

[17] Haimson, B. C. (1970). Mechanical behaviour of rock under cyclic fatigue. In Proc. 13th Symp. Rock Mech., Urbana, Illinois (pp. 845-863).

[18] Hardy, H. R. (1970). Failure of geologic materials under low cycle fatigue. In Proc. 6th Can. Rock Mech. Symp., Montreal (pp. 33-47).

[19] Attewell, P. B., & Farmer, I. W. (1973). Fatigue behaviour of rock. In International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 10(1), 1-9.

[20] Jamali Zavareh, S., Hashemolhosseini, H., Baghbanan, A., Khoshkam, M., & Haghgouei, H. (2017). Evaluating Fatigue of Intact Crystalline Rocks under Completely Reversed Loading. *Journal of Analytical and Numerical Methods in Mining Engineering*, 7(13), 91-100.

[21] Singh, S. K. (1989). Fatigue and strain hardening behaviour of graywacke from the flagstaff formation, New South Wales. Engineering Geology, 26(2), 171-179.

[22] Zhenyu, T. A. O., & Haihong, M. O. (1990). An experimental study and analysis of the behaviour of rock under cyclic loading. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 27(1), 51-56.

[23] Li, G., Moelle, K. H. R., & Lewis, J. A. (1992). Fatigue crack growth in brittle sandstones. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 29(5), 469-477.

[24] Tien, Y. M., Lee, D. H., & Juang, C. H. (1990). Strain, pore pressure and fatigue characteristics of sandstone under various load conditions. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 27(4), 283-289.

[25] Bagde, M. N., & Petroš, V. (2005). Fatigue properties of intact sandstone samples subjected to dynamic uniaxial cyclical loading. International Journal of Rock Mechanics and Mining Sciences, 42(2), 237-250.

[26] Li, N., Zhang, P., Chen, Y., & Swoboda, G. (2003). Fatigue properties of cracked, saturated and frozen sandstone samples under cyclic loading. International Journal of Rock Mechanics and Mining Sciences, 40(1), 145-150.

[27] Jamali Zavareh, S., Baghbanan, A., Hashemolhosseini, H., & Haghgouei, H. (2017). Effect of micro-structure on fatigue behavior of intact rocks under completely reversed loading. *Journal of Analytical and Numerical Methods in Mining Engineering*, 6(Special Issue), 55-62.

[28] Dalirnasab, A. , Goshtasbi, K. and Nejati, H. (2020). On the Effect of Grain Size on Rock Behavior under Cyclic Loading by Distinct Element Method. *Journal of Analytical and Numerical Methods in Mining Engineering*, 10(25), 23-32.

[29] Fuenkajorn, K., & Phueakphum, D. (2010). Effects of cyclic loading on mechanical properties of Maha Sarakham salt. Engineering Geology, 112(1-4), 43-52.

[30] Chen, Y., Watanabe, K., Kusuda, H., Kusaka, E., & Mabuchi, M. (2011). Crack growth in Westerly granite during a cyclic loading test. Engineering Geology, 117(3-4), 189-197.

[31] Fan, J., Chen, J., Jiang, D., Ren, S., & Wu, J. (2016). Fatigue properties of rock salt subjected to interval cyclic pressure. International Journal of Fatigue, 90, 109-115.

[32] Taheri, A., Royle, A., Yang, Z., & Zhao, Y. (2016). Study on variations of peak strength of a sandstone during cyclic loading. Geomechanics and Geophysics for Geo-Energy and Geo-Resources, 2, 1-10.

[33] Fan, J., Chen, J., Jiang, D., Chemenda, A., Chen, J., & Ambre, J. (2017). Discontinuous cyclic loading tests of salt with acoustic emission monitoring. International Journal of Fatigue, 94, 140-144.

[34] Jobli, A. F., Noor, M., Tawie, R., Hampden, A., & Julai, N. (2017). Uniaxial compressive strength of Malaysian weathered granite due to cyclic loading. Journal of Engineering and Applied Sciences, 12(14), 4298-4301.

[35] Liu, Y., Dai, F., Xu, N., & Zhao, T. (2017). Cyclic flattened Brazilian disc tests for measuring the tensile fatigue properties of brittle rocks. Review of Scientific Instruments, 88(8).

[36] Munoz, H., & Taheri, A. (2017). Local damage and progressive localisation in porous sandstone during cyclic loading. Rock Mechanics and Rock Engineering, 50(12), 3253-3259.

[37] Karakus, M., Ebong, U., Liu, C., & Zhou, H. (2015). Three-dimensional finite element analysis for rock fatigue damage under dynamic loading. In ISRM EUROCK.

[38] Cho, S. H., Ogata, Y., & Kaneko, K. (2005). A method for estimating the strength properties of a granitic rock subjected to dynamic loading. International Journal of Rock Mechanics and Mining Sciences, 42(4), 561-568.

[39] Murakami, Y., Takagi, T., Wada, K., & Matsunaga, H. (2021). Essential structure of SN curve: Prediction of fatigue life and fatigue limit of defective materials and nature of scatter. International Journal of Fatigue, 146, 106138.

[40] Alizadeh, R., Fatehi Marji, M., Abdollahipour, A., & Pourghasemi Sagand, M. (2021). A modified indirect boundary element analysis for fatigue behavior assessment of rock-like materials based on linear elastic fracture mechanics. Journal of Mining and Environment, 12(4), 1189-1203.

[41] Alizadeh, R., Fatehi Marji, M., Abdollahipour, A., & Sagand, M. P. (2023). Numerical simulation of fatigue crack propagation in heterogeneous geomaterials under varied loads using displacement discontinuity method. Journal of Rock Mechanics and Geotechnical Engineering, 15(3), 702-716.

[42] Dalirnasab, A., Fatehi Marji, F., Nejati, H. R., & Mohebi, M. (2024). Effects of porosity on the strength and mechanical behaviour of porous geo-materials under cyclic loading: Mechanics of Porous Geo-Materials. Rudarsko-geološko-naftni zbornik, 39(2), 15-30.

[43] Dalirnasab, A. , Fatehi Marji, M. , Nejati, H. R. and Mohebbi, M. (2024). Investigating the effects of porosity on the strength and mechanical behaviors of geo-materials' specimens. *Journal of Analytical and Numerical Methods in Mining Engineering*, 14(39), 1-12.

[44] Brown, E. T., & Hudson, J. A. (1973). Fatigue failure characteristics of some models of jointed rock. Earthquake Engineering & Structural Dynamics, 2(4), 379-386.

[45] Cruden, D. M. (1974). The static fatigue of brittle rock under uniaxial compression. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 11(2), 67-73.

[46] Ray, S. K., Sarkar, M., & Singh, T. N. (1999). Effect of cyclic loading and strain rate on the mechanical behaviour of sandstone. International Journal of Rock Mechanics and Mining Sciences, 36(4), 543-549.