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REPEATED LOADING OF THE SALEM LIMESTONE (INDIANA LIMESTONE; MISSISSIPPIAN)

Nils I. Johansen
Mining and Geological Engineering
University of Alaska Fairbanks
Fairbanks, Alaska 99775-5800

ABSTRACT: This paper describes a model for predicting the life expectancy of a rock specimen subjected to repeated loading. A case study based on data obtained from samples of the Salem Limestone (Mississippian) is used to test the hypothesis. The results are summarized in such a way that a "one-point fatigue test" can predict service life at a given stress level.

KEYWORDS: Rock mechanics, fatigue testing, strength predictions.

INTRODUCTION

The fact that a rock will break when struck repeatedly is hardly a new concept. Paleolithic man shaped tools using this principle, and many a cornfield in Indiana is littered with flint or chert flakes from arrowhead manufacturing. In 1881, Thomas H. Johnson reported, "It is well known that a stone however large may be broken by striking a sufficient number of blows with a hammer along a line where it is desired to break the stone. In this process, the force of the blows is expended in gradually weakening the cohesion of the particles in a line following the direction of the blow, until finally rupture occurs." This deterioration of rock strength, where repeated load applications finally break the sample, is illustrated in Figure 1. The author proposes that this gradual breakdown of internal rock structure can be used to predict the fatigue behavior of the rock. Similar research was carried out in France by Bernaix (1974).

MATERIALS AND METHODS

A model is described in this paper, based on a re-analysis of old test data (Johansen, 1971), for predicting the number of load cycles a rock sample can withstand in uniaxial compression. The volumetric strain-uniaxial stress curve rather than the typical uniaxial stress-strain curve was used to predict fatigue behavior. Data from a case study on the Salem Limestone were utilized to develop a graph from which to predict the rock's fatigue behavior. The samples were sawed from a single block of limestone donated by a quarry near Bedford. The samples had nominal dimensions of 2 in. x 2 in. x 5.5 in., and the direction of the bedding was along the long axis of the sample.

FAILURE MECHANISM AND ENERGY CONSIDERATIONS

The uniaxial stress-volumetric strain curve gives a good representation of the internal changes that take place in a rock sample as an increasing uniaxial load is

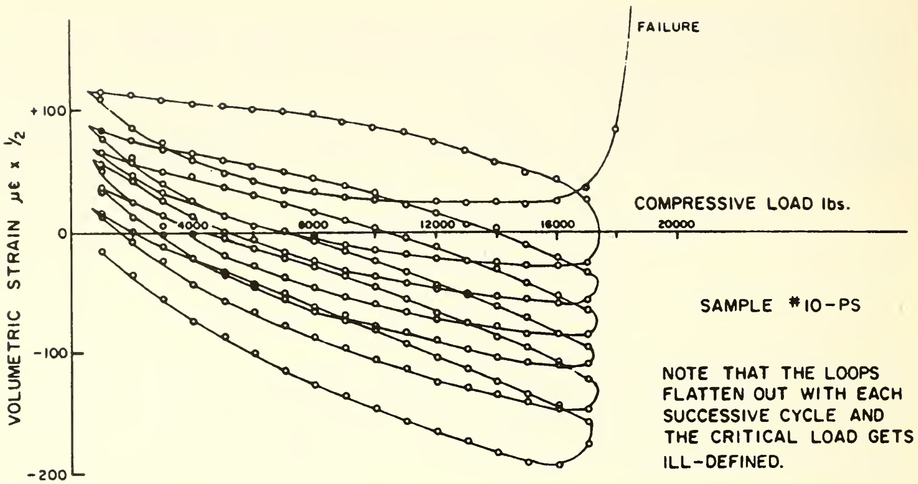

Figure 1. The deterioration of rock strength with repeated load applications.

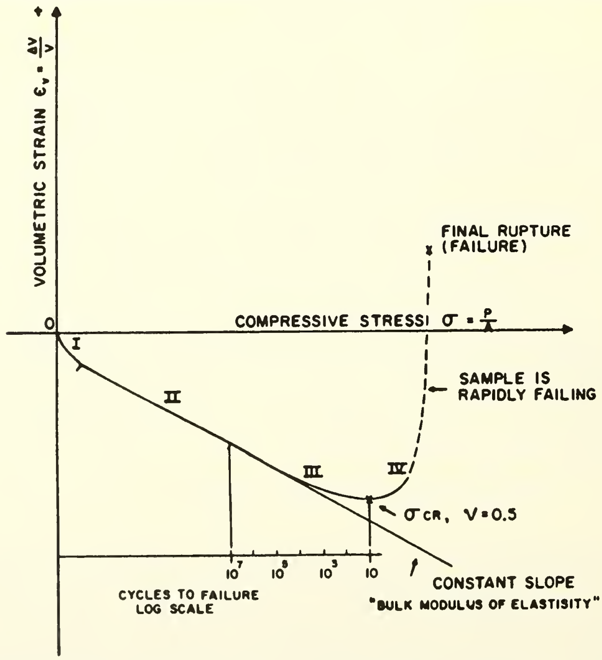

Figure 2. The stress-volumetric strain curve for uniaxial compression.

applied. This process was described by Brace (1963) and was used as part of this study to establish the behavior characteristics of rock (Johansen, 1971).

When a uniaxial load is applied, initially the internal flaws or cracks will close, resulting in a non-linear volume reduction. This process occurs in Region I (Figure 2). Region II depicts the almost linear relationship between uniaxial stress and volumetric strain that follows as the load is increased. Region III shows progressively non-linear behavior due to a change in Poisson's ratio leading to

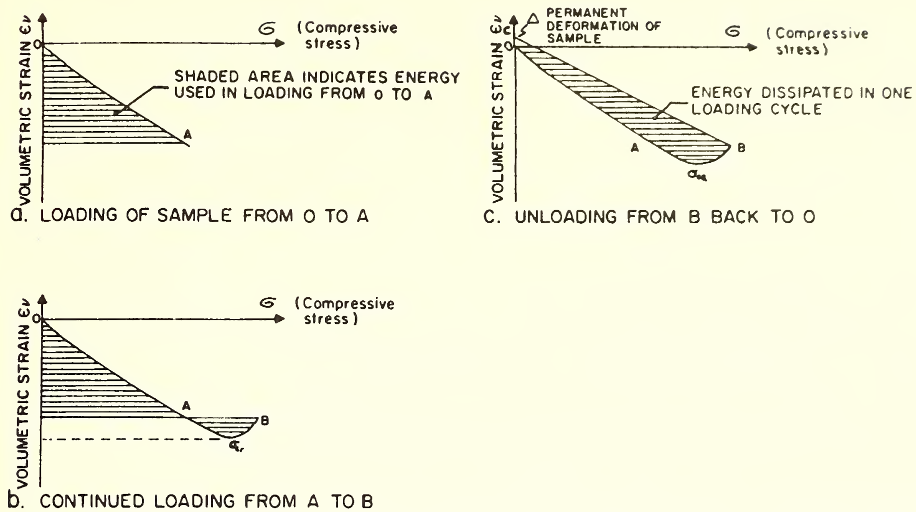

Figure 3. Energy considerations for a stress-volumetric strain curve.

different rates of strain increase in the directions parallel and perpendicular to the axis of applied stress. The volumetric strain curve being the sum of the linear strains will hence be curved as the individual strains increase at different rates. When the differential movement along the shear planes becomes so great that the strength of the rock fabric is exceeded by the stresses in the tips of the cracks formed as the load is applied, the cracks will become self-propagating. If the energy input is greater than what can be dissipated by a single crack, the crack will bifurcate. The process of crack forking is a major contributing factor to the volume change that occurs in Region IV. The fracture process becomes continuous and self-sustaining, and the sample fails. Region IV is known as the region of unstable crack propagation, and here, the internal integrity of the sample is destroyed. Individual parts of the sample can now move independently of each other. The sample undergoes a significant increase in volume, when there is only a minute increase in the applied compressive stress. The volume measured at this point is no longer the volume of the rock sample but the volume of the rock sample plus the volume of the induced fractures. Actually, the rock sample has already failed with the onset of unstable crack propagation. At this load or stress level, it is just a matter of time before physical disintegration of the sample occurs.

Figure 3 also shows that fracturing is a function of the energy input into the sample, since the units along the coordinate axes represent stress (psi) and strain (in/in), respectively. The area within the hysteresis loop has units of in-lb/cubic in or energy per unit volume. The failure process can be thought of as a progressive dissipation of the energy induced by the applied load.

ENERGY DISSIPATION PROCESS

Figure 3c is the stress-volumetric strain curve, representing the energy lost in the specimen (shaded area) as the load is cycled. Upon reloading to the stress level at point B, the curve closely follows the unloading curve until it exceeds the

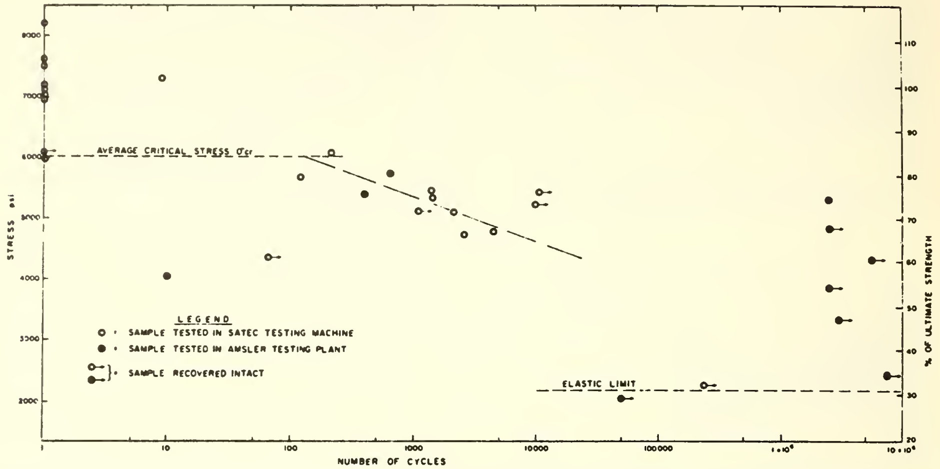

Figure 4. Stress as related to the number of load cycles (S-N curve) for 33 samples of the Salem Limestone.

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maximum load imposed in the previous cycle. Figure 1 shows that the energy dissipated during each loading and unloading cycle reduces the area between the volumetric strain curve and the axial stress axis. The total number of cycles needed to fail the specimen may be estimated by dividing the total area between the initial curve and the stress axis by the area within each subsequent hysteresis loop. This value is a measure of the energy loss per cycle (Figure 1).

A problem arises when the area within the hysteresis loop is too small to be readily computed. The solution is provided by the stress-strain curve itself. The curve clearly shows the upper limit of the bulk elastic region as the point where the curve deviates from the straight line portion of Region II. For the Salem Limestone, the point was determined to be 35% of the ultimate uniaxial compressive strength. The samples tested show that repeated loads to this level or less can be applied 10 million times or more (Figure 4).

Another clearly defined point is the critical point (Figure 2). At this stress level, s cr Poisson's ratio is 0.5. No volume change occurs with an increase in compressive stress. The fatigue life at this level, about 85% of the short-term ultimate stress, is of the order of ten to one hundred cycles, depending on the speed of the load applications. The theoretical lower limit, as already discussed, is one cycle or load application.

In order to measure fatigue life in terms of the number of load applications to a given level and avoid the problem of measuring small hysteresis loops, an estimate of the fatigue life can be made directly from the original stress-strain curve. The method is shown in Figure 2. A log scale is introduced over Region III, ranging from 10 million at the start of Region III to ten at the end of the Region. The load level (from the log curve imposed over Region III) gives an estimate of the number of times the rock sample can be loaded to that level.

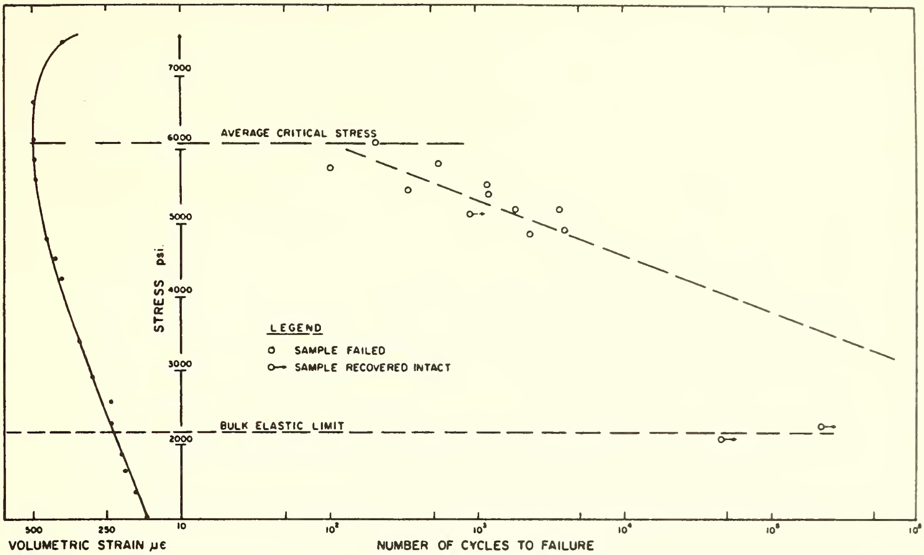

Figure 5. A composite graph showing the relationship between stress level and the corresponding volumetric strain and number of cycles to failure for the Salem Limestone (33 samples).

TEST OF THE MODEL

Figures 4 and 5 summarize the test results for limestone prisms repeatedly tested to various load levels. Figure 4 shows a typical stress to number of cycles curve (S-N curve) for failure of 33 samples from the Salem Limestone. Figure 5 combines these tests with a stress-volumetric strain curve creating a model that can be used for predicting fatigue behavior for this limestone under uniaxial repeated loads. For a given stress level in Region III, the graph gives an estimate of the number of load applications to this level that the sample can be expected to withstand. The curve in Figure 5 can be thought of as a one-point fatigue test. This is again shown in Figure 1.

The curve does, however, have limitations. Adjustments must be made for other types of load applications and, of course, different rock types.

CONCLUSIONS

The proposed model has been shown to predict the long-term fatigue behavior of a limestone subjected to uniaxial repeated loading to a given load level. The model predicts the number of cycles a specimen may withstand at this load level, in effect providing a measure of the long-term life of the rock structure at this stress or load level.

The stress-volumetric strain curve gives a far superior picture of rock behavior than a regular stress-strain curve. The Poisson effect is readily detected in the stress-volumetric strain curve, and the true elastic region can be readily identified.

By directly monitoring the volumetric strain as the sample is loaded, an accurate appraisal of rock strength can be made in any given instance. Rock samples subjected to repeated loading within the bulk elastic region (Region II) will withstand a very large number (greater than 10 million) of load applications. The upper limit of the bulk elastic region is approximately 35% of the conventional, ultimate strength of the Salem Limestone.

Repeated loading past the bulk elastic region as measured from the stress-volumetric strain curve will cause a gradual, progressive failure of the rock specimen. At stress levels greater than the upper limit of the bulk elastic region, a progressive increase in the internal fracturing of the sample occurs. Upon unloading from a stress at this level, the sample shows permanent deformation.

Poisson's ratio changes continuously but exhibits a reasonably constant value in Region II, the bulk elastic region. As the stress level increases, Poisson's ratio increases reflecting the different increases in lateral and axial strain, and the long-term, maximum strength value is the critical stress. At this point, maximum volumetric strain occurs. The point is also characterized by a Poisson's ratio of 0.5 or yield under constant volume. Repeated loading to a stress level greater than the critical stress does not give meaningful results in terms of fatigue life. The sample has essentially failed at this point.

LITERATURE CITED

Brace, W.F. 1964. Brittle fracture of rocks. In: W.R. Judd (Ed.), *International Conference on State of Stress in the Earth's Crust,* pp. 111-178, Amer. Elsevier Publ. Co., New York, New York, 732 pp.

Bernaix, J. 1974. Properties of rock masses. Proc. Third Congr. Int. Sec. Rock Mechanics, Nat. Acad. Sci., Washington, D.C., pp. 9-38.

Johansen, N.I. 1971. The influence of previous stress history upon strength and creep properties of limestone. Ph.D. Thesis, Purdue Univ., 203 pp.

Johnson, T.H. 1881. Experiments upon the transverse strength and elasticity of building stones. Indiana Dep. Geol. Natur. Hist., 11th Annual Report, pp. 34-46.