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Recent Advances in Fracture Mechanics with Applications in Petroleum Engineering

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Introduction

Basic fracture mechanics ideas are reviewed to assess their use in simulating fracture initiation and propagation during hydraulic fracturing and water flooding. Recent breakthroughs in fracture modeling and quasi-equilibrium growth are discussed. The role of the process zone in fracturing is given special consideration. The differences in simulated and measured net fracture pressures may be explained by the process zone found in laboratory and field hydraulic fracture tests. The shared key element for proposed methods utilized for calibrating hydraulic fracture models is discovered to be the process zone. There is a discussion of deterministic and probabilistic causes in fracture phenomena. The consequences of scale and pace are examined.

Introduction

Material failure and fracture have long been a source of worry for scientists and engineers. Classical strength requirements were developed in the nineteenth century based on mechanical testing. These empirical criteria are based on the tested specimen's average stress, strain, or energy in the critical stage of failure to define a material attribute that evaluates the strength of the tested material. These simple criteria have been effectively applied in engineering designs in numerous practical applications. A series of catastrophic disasters in engineering constructions in the 1950s demonstrated the limits of the design philosophy. A further examination of these examples revealed the failure localization and fracture propagation that had previously been overlooked by traditional models.

Linear Elastic Fracture Mechanics (LEFM) was created to investigate fracture propagation caused by substantial elastic energy stored in a material with tiny fissures. As a result, the crack extension force for abrupt fracture propagation equals the energy release rate, GI. As a result, its critical values, GIc, at the commencement of crack propagation and fracture instability are taken as a measure of material toughness and empirically tested. Early fracture studies revealed that GIc does not depend on loading configuration, sample geometry, or crack size in some semi-brittle materials, implying that it is a material feature. High local stresses near the crack tip generate a limited failure zone in such materials that remains unaltered during fracture testing, hence the specifics of the failure mechanism are unimportant. A similar technique based on stress intensity factor, KI, whose critical value, KIc (also known as fracture toughness), specifies material resistance to crack propagation, was presented to simplify engineering calculations. GIc or KIc, the roughness parameters, must be tested experimentally. Where fracture propagates stably in many materials, fracture resistance fluctuates with crack expansion, displaying so-called R-curve behavior, when crack resistance cannot be described by a single quantity.

This clearly illustrates that fracture toughness is not a material constant in general, and fracture development prediction requires a more detailed understanding of the failure process. It also proposes that any hypotheses that predict fracture development using LEFM criteria be re-evaluated.

The advancement of fracture mechanics in recent decades has resulted in a far better knowledge of the micromechanisms that cause failure. This paper discusses some recent breakthroughs in the research of fracture mechanisms in diverse materials. The process zone's involvement in fracturing is given special consideration. The fracturing phenomenon is modeled in two ways (deterministic and probabilistic). The deterministic approaches reflect the localization of fracture associated with the stress concentration, whereas the probabilistic approaches reflect the scatter of the observed fracture parameters caused by the heterogeneous nature of the rock mass, random distribution of the initial defects, and material characterization limitations.

The processes that influence hydraulic fracture initiation and propagation are discussed. It is discussed the role of the Process Zone (PZ) seen in laboratory and field Hydraulic Fracture (HF) tests. Several tip mechanisms reported in the past to explain variations in simulated and field net fracture pressures and are now employed for HF model calibration are analyzed. The shared key ingredient for various tip mechanisms is shown to be the process zone. The impacts of scale and rate in HF are examined. Some field applications that would benefit from a better knowledge of the HF process are discussed.

Hydraulic Fracture Beginning

Fracture initiation in open, cased, and perforated boreholes is a critical issue in HF stress measurements and stimulation. Despite noted doubts regarding the validity of this method, the breakdown (or reopening) pressure is frequently employed to calculate intermediate horizontal stress in HF stress measurements. Severe Near-WellBore (NWB) flow constraints are reported in the field during HF stimulation, causing difficulty linking the wellbore with far-field HF and jeopardizing the capacity to insert proppant in the fracture during fracture treatments. Field experience also reveals that when wellbores severely deviate, constraints are more severe and frequent, and the injection rate during the breakdown is low relative to the matrix leak-off rate. Some limited field research implies that these NWB difficulties may be caused by numerous fractures or fracture reorientation.

Laboratory studies of HF initiation support this hypothesis by identifying complex HF geometry near the wellbore, such as multiple fractures initiated from perforations, T-shaped fractures surrounding the open hole, and step-wise or gradual fracture reorientation from the wellbore to a planar fracture perpendicular to the minimum stress. One of the probable causes of NWB flow constraints is the intricate fracture geometry. The fracture geometry at initiation is heavily influenced by borehole orientation in the in-situ stress field, as well as injection rate and fluid viscosity, among other things. The limited data on the rate effect on NWB fracture geometry is contradictory: some studies suggest that lower injection rates result in fewer multiple fractures, while others suggest that higher rates with more viscous fluids result in more gradual fracture reorientation and less multiple fracturing. The later findings back up the field observations. Attempts have been made to investigate the mechanism of fracture reorientation following the breakdown. The fracture reorientation process was determined to be caused by a combination of shear failure and tensile fracture development.

By minimizing or eliminating the NWB flow choke through proper field breakdown procedures, you can lower the HF treating pressures (and thus the cost of HF treatment), reduce the risk of NWB sand out (the most common cause of treatment failure), and increase the production rate by minimizing non-darcy NWB effects. These economic benefits justify a more in-depth examination of this issue.

Fracture maps

Many attempts to develop a better failure criterion have resulted in a wide variety of proposed strength criteria based on stress or strain tensor components. This high number of failure criteria demonstrates a basic lack of knowledge of failure situations.

The relatively recent invention of fracture mechanism maps dispels the erroneous notion of a single universal strength requirement. Similarly, linear and non-linear fracture mechanics crack resistance criteria based on critical stress intensity factor, critical crack-tip opening displacement, critical energy release rate, and so on are restricted in applicability since they do not take into account the actual fracture mechanisms. The major takeaway from fracture mechanism maps is that many modes of failure exist for the same material, each with its particular strength or fracture propagation threshold.

Detailed investigations of fracture initiation in diverse structural materials demonstrate that distinct mechanisms of failure influence fracture initiation depending on loading history and temperature. In metals, for example, depending on the temperature, the processes of crack initiation in tension are cleavage, ductile fracture, transgranular or intergranular creep fracture, and so on. Material toughness, G1c, can vary by orders of magnitude for these different failure mechanisms, ranging from, ~1 J/m2 when the material fails in brittle cleavage to more than 106 J/m2 when the material fails in plastic rupture.

Hydrolic Fracture Propagation

Over the last decade, critical examination of Hydraulic Fracture (HF) treatments has revealed widespread inconsistencies between field findings and theoretical predictions based on LEFMA. The facts that the measured field net fracture pressure is more than what HF simulators can anticipate and that the net pressure is quite insensitive to rate variation and fluid viscosity are the most essential for the following discussion. Furthermore, limited direct observations of HF indicate that hydraulic fracture may be a zone of multiple fractures produced in locally heterogeneous rocks and somehow connected to form a large hydraulic fracture. Although the precise origins of these field findings are unknown, they hint at intricate mechanisms near the fracture tip as the most plausible explanation for the observed disparities.

To explain these disparities, many tip mechanisms are proposed. These are caused by (1) fluid lag regulation near the fracture tip, (2) nonlinear rock deformation and dilatancy at the fracture tip, and (3) a complex rate- and scale-dependent process zone surrounding a propagating hydraulic fracture. Any of the tip mechanisms increases the formation resistance to hydraulic fracture propagation at its tip by allowing net pressure to build up there and making the pressure profile in the main section of the fracture more uniform. Several recent papers have examined these explanations in depth. Additional comments on the similarities and contrasts. There should be some debate about the relationship between these "near-tip processes" and their implementation into numerical HF geometry simulators for field designs.

Toughness to fracture

The method acknowledges that fracture toughness is not a material constant and can be affected by scale and rate effects. This supports using fracture toughness as a calibration parameter in simplified HF models to avoid the most significant inconsistencies between HF field test results and classical HF models used in field HF treatment design. The observed disparities are attributed to the process zone, while other tip variables are grouped under apparent fracture toughness. Other elements, such as the sophisticated connection between rock deformation and fluid flow at the tip, are necessary for the correct simulation of 3-D fracture geometry, but the current limited understanding of tip dynamics does not warrant an increase in model complexity. As a result, 3-D geometry simulation (i.e., prediction or fracture containment) was not tried using this method. Calibration of 2-D HF models accommodates for potential increases in net fracture pressure towards the fracture tip and makes pressure profiles in the fracture more uniform while lowering the susceptibility of fracture geometry and simulated net pressures to fluid viscosity, as seen in the field. Because they adequately rectify the key volumetric inaccuracies of standard HF models, these models have been employed successfully in field applications. Field studies have shown that the fracture toughness required for calibrating HF models is typically an order of magnitude more than that observed in laboratory trials. This finding, together with the discoveries that calibrated fracture toughness is rate-dependent and varies with fracture length, drew harsh criticism. Furthermore, the net pressure observed during the initial injection, when HF is being produced, typically does not alter during subsequent injections, when existing HF is being re-opened. This contradiction appears to refute the fracture toughness argument because it contradicts our understanding of fracture toughness, which is based on experience with the fracture behavior of structural materials in tension.

Fluid lag region

The calibration method also takes into consideration viscous flow in the main area of the fracture, which might cause the fracture to develop after shut-in. The main tip effect is thought to be an accurate connection of rock elastic deformation and fluid flow at the fracture tip. This effect has played a significant role in the development of analytical, semi-analytical, and computational 2- and 3-D HF models. As part of the solution, the most advanced models anticipate the amount of the fluid lag and the pressure distribution in the crack. For fracture diameters of tens of meters, these completely linked solutions offer a somewhat uniform pressure distribution in the major body of the fracture and a very fast decrease towards the fracture tip at distances of a few centimeters or less. According to the simulations, fracture shape can change dramatically after shut-in.

However, these models frequently replicate too high net pressures during early injection and too low net pressures for big poorly confined fractures later on. Any attempt to match established HF field net pressure would necessitate some artificial increase in the fluid lag zone or formation stiffness.

Tip-dilatancy

A proposed mechanism lacking in the pure elastic fluid lag models above is inelastic rock behavior near the fracture point. Ahead of the fracture tip, where local deviatoric stress is expected to be very high, the rock may plastically deform, causing rock dilatancy and constraining the opening, leading to increased resistance to fluid flow to the fracture tip and a build-up of net pressure in the main part of the fracture. By modifying a few model parameters, this hypothesis has been effectively applied in the field to calibrate a fully linked HF model to net fracture treatment pressure.

To evaluate the influence of tip dilatancy, direct finite element simulations of inelastic deformation at the fracture tip were done, either completely linked or de-coupled with fluid flow in the crack. These simulations indicate that when lab-measured inelastic rock parameters are utilized as input, the simulated rock failure occurs in a limited zone around the fracture tip, resulting in a minor change in net fracture pressure (in compared to a pure elastic solution). In such calculations, the plastic failure zone and net fracture pressure can be increased if rock strength features, such as cohesive modules, are considered to be lower than observed in the lab. This appears to imply that tip dilatancy can impact net pressure only if the features of non-linear deformation and rock mass failure are susceptible to a strong scale effect, which may be difficult to anticipate solely on laboratory data. As a result, the model needs field calibration.

Mechanics of continuum damage

To represent inelastic rock behavior near the fracture tip, the concept of continuum damage mechanics (CDM) was recently proposed. In general, the model employs two parameters: C for damage and l for size. In the field, the model for confined fracture is straightforward since it commonly employs a single combined parameter (Cl2) to match net fracture pressure. This may therefore be connected to KI and, as a result, to the apparent fracture toughness stated above. When calculated in laboratory and field circumstances, the combined parameter differs by four orders of magnitude, which is explained by changes in the scale parameter, l, which is explicitly employed in the model. Matching both early and late temporal pressure data can need distinct estimations of C and l.

Conclusion

We discussed the shortcomings of universal fracture propagation criteria in linear and nonlinear fracture mechanics, as well as recent developments in modeling fracture initiation and quasi-equilibrium growth. We devoted special attention to the process zone's involvement in fracturing. The differences in simulated and measured net fracture pressures may be explained by the process zone found in laboratory and field hydraulic fracture tests. The process zone has been demonstrated to be the universal crucial element for various tip mechanisms utilized for calibrating hydraulic fracture models. PZ seems to be sensitive to a variety of scale and rate factors, which greatly challenge the realistic modeling of fracture geometry, particularly fracture containment. We discovered possible deterministic and probabilistic factors influencing HF development. These processes must be investigated in both laboratory and field hydraulic fracture tests. This hard and costly study is justified by the immense economic benefits of their possible achievements in the petroleum sector and other geomechanics domains.

The paper describes some of these uses. We uncovered deterministic and probabilistic elements that may influence HF development. Hydraulic fracture studies in the laboratory and the field must be conducted to explore these processes. The enormous economic benefits of their potential successes in the petroleum sector and other geomechanics fields justify this difficult and costly study. Some of these applications are discussed in the article. It appears that at this moment, research into fracture processes can provide a new level of understanding of HF and drive future advances of this interesting technology in a variety of sectors and applications.

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