



A Paradigm Shift in Dam Engineering: Universal Failure Prediction Using the Breaking Stress Criterion

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ABSTRACT

Predicting when and how materials fail continues to be a central challenge in engineering, especially in the context of massive infrastructure such as dams, where failure can result in catastrophic outcomes. Conventional design codes and empirical failure models often misrepresent structural capacity, creating uncertainty in both safety and performance. In this work, the Breaking Stress Criterion—a recently formulated, single-parameter failure principle that extends classical elasticity—has been employed to assess dam stability. The criterion integrates external loads with internal stress states by defining failure through the peak internal breaking stress, represented geometrically as a spherical surface in principal stress space. To evaluate this, advanced finite-element simulations were conducted in ABAQUS, where the dam was modeled with higher-order continuum elements under realistic hydrostatic pressures and boundary conditions. The analysis revealed that boundary conditions play a decisive role in shaping stress concentrations and determining failure zones, highlighting the limitations of relying solely on Saint-Venant's assumptions. The approach successfully linked applied loads to internal breaking stresses, with failure predicted at a surface pressure of 1.5 MPa corresponding to a breaking stress of 160 MPa. These results reinforce the Breaking Stress Criterion as a robust and broadly applicable measure of failure for isotropic, homogeneous, and incompressible materials, providing engineers with a reliable framework for designing dam structures that are safer, more resilient, and cost-effective.



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A Look Down the Road: Material Failure as an Enduring Challenge

Understanding how and why materials fail has long stood at the core of engineering thought and practice. From humanity's earliest reliance on stone, timber, and soil to build shelters and infrastructure, the consequences of collapse have been both practical and profoundly human. History is marked by disasters where the limits of material strength—misjudged, overlooked, or misapplied—led to tragic outcomes. The South Fork Dam disaster of 1889, which caused the Johnstown Flood and claimed more than 2,200 lives, and the Brumadinho tailings dam failure in Brazil in 2019, illustrate that material failure is not an abstract technical issue but one with immediate human and environmental repercussions.

Despite centuries of progress in mechanics and materials science, the theoretical basis for predicting failure under complex or multiaxial stress states remains unsettled. Engineers still rely heavily on empirical or ad hoc criteria that are often disconnected from fundamental physical principles. This gap raises doubts about the reliability of current approaches. Would anyone have trusted early experimental aircraft when aeronautical science was still in its infancy, or confidently relied on structures built from unconventional materials without a sound theoretical framework? The recurring tragedies of material failure highlight the urgency of developing a robust and universal theory.

Even with advances in computational mechanics and the widespread use of finite-element methods, skepticism persists. As Christensen (2016) noted, many of the criteria in use today are relics of earlier eras, inadequate for modern applications and contributing to a pessimistic outlook in the field. The discipline risks stagnation if it continues to depend on outdated assumptions.

The history of failure theories is littered with attempts that proved partial or incorrect, leaving fundamental questions unresolved: How can valid criteria be distinguished from flawed ones? Is there truly a need for yet another failure model, or can a general theory finally emerge as the long-sought counterpart to elasticity? If such a theory exists, can it be formulated broadly enough to serve across diverse engineering domains? These are not merely academic inquiries—they strike at the heart of one of the most enduring challenges in mechanics. Physically grounded failure criteria for homogeneous materials have often been described as among the most difficult problems in engineering science.

Why, then, might the present era be different? One reason lies in the limitations of traditional validation

methods. Large-scale testing of dams, bridges, or aircraft is neither practical nor economically feasible. Instead, engineers must rely on small-scale experiments, mathematical models, and advanced numerical simulations to extrapolate structural behavior. This reliance on analytical and computational tools prompts a critical question: can elasticity theory, when integrated with modern finite-element analysis, provide the foundation for a universal failure criterion that is both rigorous and applicable in practice?

The ultimate goal is not only to predict failure with precision but also to enable the design of structures that are safer, more resilient, environmentally responsible, and economically efficient. Pursuing such a theory is far more than an academic endeavor—it is essential for advancing engineering practice in an age where unconventional materials and innovative systems are increasingly deployed in critical infrastructure such as dams.

The One-Parameter General Failure Theorem Retracted, EL HAJJ (2023) The Breaking Stress Criterion introduces a one-parameter general failure theorem that complements elasticity theory and provides a universal framework for predicting material failure. Validated through finite-element analysis, it demonstrates applicability across diverse materials and structural systems, offering more accurate predictions than existing design codes. By linking external forces to internal breaking stresses, it establishes a unified criterion for determining structural capacity under realistic boundary conditions, paving the way for safer and more innovative designs.

The Breaking Stress Criterion represents a significant advancement in failure mechanics, challenging long-standing assumptions and offering a unifying principle that reshapes how engineers evaluate structural safety. Conceived as the long-missing counterpart to elasticity theory, it establishes a true one-parameter general failure criterion, addressing a problem that has persisted since the early formulations of Coulomb, Mohr, von Mises, and Drucker-Prager.

At its core, the study introduced a methodology that identifies this one-parameter criterion as the only general failure theory applicable to noncompressible, homogeneous, and isotropic materials subjected to multiaxial stress states and diverse boundary conditions. The criterion is expressed in a formalism broad enough to be applied across a wide range of materials—including concrete, metals, polymers, glasses, and rocks—and to both small-scale and large-scale structural systems.

The contribution was twofold. First, it presented the governing equation for the proposed criterion and outlined a systematic procedure for failure identification using advanced finite-element analysis (ABAQUS). That approach emphasized the importance of distinguishing between the stress-strain behavior observed in experiments and the intrinsic material response, while also incorporating realistic modeling assumptions and micro-level stress interpretations. Second, the study validated the criterion through practical applications, showing its effectiveness in capturing the service-limit structural capacity of conventional elements and its potential for analyzing unconventional systems.

A critical comparison with established design codes revealed substantial discrepancies. For example, ACI 318-19 provisions could underestimate capacity by up to 2.17 times or overestimate it by 2.096 times, while ANSI/AISC 360-16 could underestimate by 1.4 times or overestimate by 2.49 times. These findings highlight the limitations of current code-based approaches and underscore the need for a more universal and physically grounded criterion.

The research further demonstrated that boundary conditions play a decisive role in determining stress concentrations, failure locations, and overall structural capacity. Unlike conventional analysis, which often assumes uniform stress distributions away from load application points (as per Saint-Venant's principle), the Breaking Stress Criterion—implemented through advanced FEA—captured the true influence of boundary effects.

Ultimately, the study articulated a clear relationship between externally applied forces and internally developed breaking stresses, identifying the maximum internal breaking stress as a universal measure of structural capacity. This unified approach provides engineers with a powerful tool for designing both conventional and unconventional systems, marking a potential paradigm shift in structural mechanics and design practice.

Now that the complete theory of materials failure is derived, it is about time to move to other priorities. The heart of this study is the application of The Breaking Stress Criterion for the structural analysis of a dam, where the hydrostatic forces play a pivotal role in the stress distribution within elements.

To understand the internal stress state of a material element, consider a box-shaped volume aligned with the global coordinate axes (x, y, z). Within this element, the stress components are assumed to be uniformly distributed. Classical elasticity theory describes the

internal forces acting on the faces of this element using six independent stress components: three normal stresses and three shear stresses. These are expressed as vector quantities on planes perpendicular to each axis:

$$\sigma_x = \sigma_{xx}\vec{i} + \sigma_{xy}\vec{j} + \sigma_{xz}\vec{k}$$

Equation (1)

$$\sigma_y = \sigma_{yx}\vec{i} + \sigma_{yy}\vec{j} + \sigma_{yz}\vec{k}$$

Equation (2)

$$\sigma_z = \sigma_{zx}\vec{i} + \sigma_{zy}\vec{j} + \sigma_{zz}\vec{k}$$

Equation (3)

While this six-component formulation is comprehensive, it becomes impractical for general failure analysis—especially under complex loading conditions. For simple cases, such as uniaxial stress, assumptions can be made to simplify the analysis. However, for multiaxial stress states, a more efficient representation is necessary.

In such cases, the stress state can be transformed into a set of three mutually orthogonal planes where shear stresses vanish. The remaining normal stresses on these planes are known as the principal stresses: . These are obtained by solving the characteristic cubic equation:

$$\sigma^3 - I_1\sigma^2 + I_2\sigma - I_3 = 0$$

Equation (4)

Where I_1 , I_2 , and I_3 are the three stress invariants given by:

$$I_1 = \sigma_{xx} + \sigma_{yy} + \sigma_{zz}$$

Equation (5)

$$I_2 = \begin{vmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{vmatrix} + \begin{vmatrix} \sigma_{xx} & \sigma_{xz} \\ \sigma_{zx} & \sigma_{zz} \end{vmatrix} + \begin{vmatrix} \sigma_{yy} & \sigma_{yz} \\ \sigma_{zy} & \sigma_{zz} \end{vmatrix}$$

Equation (6)

$$I_3 = \begin{vmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{vmatrix}$$

Equation (7)

Although principal stresses offer a reduced representation, failure criteria based solely on these three parameters have not achieved universal acceptance. This raises the question: can the state of stress be distilled into a single scalar quantity that governs failure?

Fortunately, such a simplification is possible through the concept of octahedral stress planes—eight symmetrically oriented planes within the material where stress components can be resolved into:

Octahedral Normal Stress:

$$\sigma_{oct} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}$$

Equation (8)

Octahedral shear Stress:

$$\tau_{oct} = \frac{\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}}{3}$$

Equation (9)

More complete discussions of principal stress and octahedral stress theory are presented elsewhere (Boresi et al.2010). Here, we merely present the main equations.

Having these two octahedral stress components, the state of stress can be described using one component that is the result of the two. The proposed component will be denoted by breaking

The proposed component will be denoted by the breaking stress (σ_{br}) and is given by:

$$\sigma_{br}^2 = \sigma_{oct}^2 + \tau_{oct}^2$$

Equation (10)

Substituting the expressions for σ_{oct} and τ_{oct} ,

the breaking stress simplifies to:

$$\sigma_{br} = \sqrt{\frac{\sigma_1^2 + \sigma_2^2 + \sigma_3^2}{3}}$$

Equation (11)

This equation represents a spherical failure surface in principal stress space and serves as the only known one-parameter general failure criterion for noncompressible, homogeneous, and isotropic materials under multiaxial loading and varied boundary conditions. Failure is predicted to occur when the computed breaking stress at any point equals or exceeds the material's intrinsic breaking strength.

This formulation not only simplifies the complexity of multiaxial stress analysis but also fills a critical gap in elasticity theory by providing a physically and mathematically grounded criterion for structural failure.

Methodology: Applying the Breaking Stress Criterion to Dam Analysis

Overview

This section outlines the analytical framework used to evaluate the structural integrity of a dam using the Breaking Stress Criterion. The approach integrates elasticity theory with advanced finite-element modeling to identify the maximum internal breaking stress under multiaxial loading conditions. The criterion serves as a universal failure measure for noncompressible, homogeneous, and isotropic materials—such as concrete and rock—commonly used in dam construction.

Finite-Element Modeling Strategy

The 40 m * 40 m dam structure is discretized using higher-order continuum 20-node quadratic brick, reduced integration elements (C3DR20) within ABAQUS 2017 software. The mesh is refined in regions expected to experience stress concentration, such as near spillways, foundation interfaces, and abutments. Material properties are assigned based on linear elastic behavior, with modulus of elasticity (E=35GPa) and Poisson's ratio (ν=0.2) calibrated from experimental data.

Boundary Conditions and Loading

Fixed boundary conditions are imposed at the bottom and left and right edges of the assembly to reflect the interaction between the dam and its foundation and edges. Loading is applied incrementally using applies pressure on a mapped analytical field to capture the nonlinear response of the structure under increasing hydrostatic pressure (Figure 1).

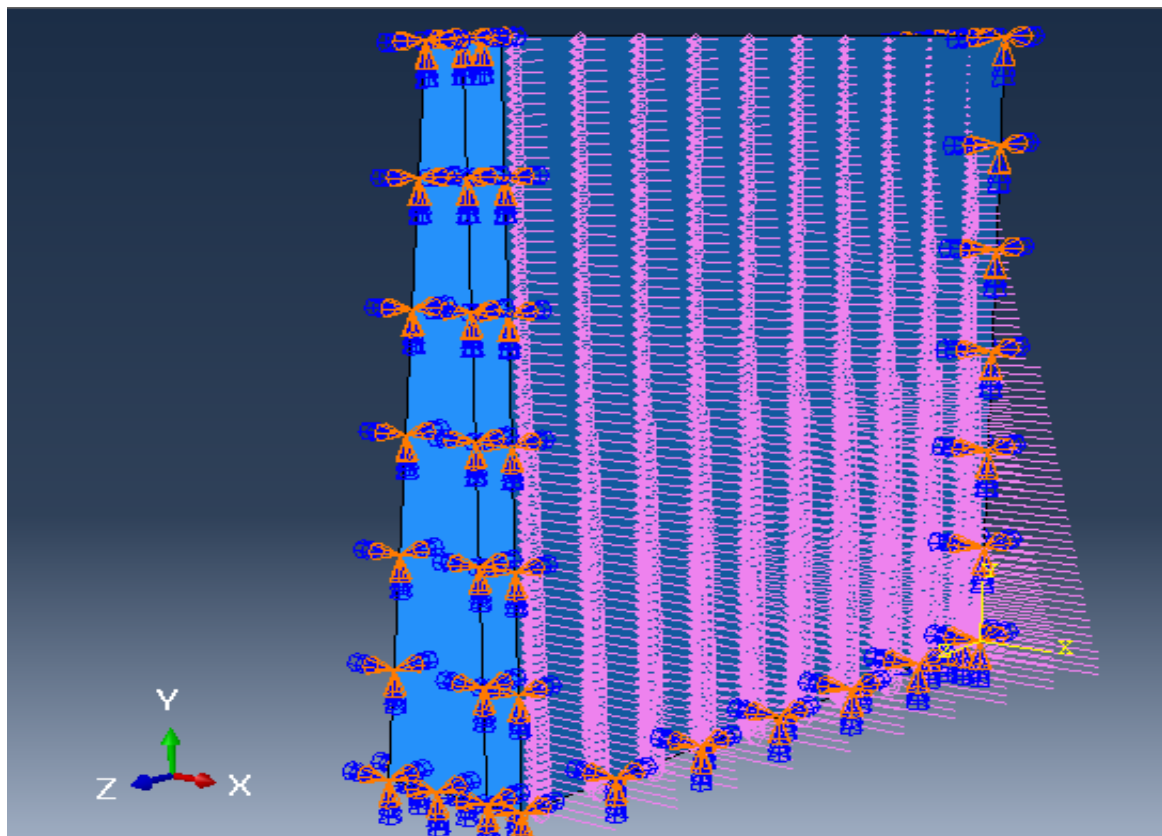


Figure 1. Boundary Conditions and Loading Applied to The Considered Dam

Stress Evaluation and Failure Identification

At each increment, the principal stresses are extracted at critical points within the dam. These are used to compute

The Octahedral normal stress, The Octahedral shear stress, and The Breaking stress.

Failure is predicted when the breaking stress by ALI NOUR EL HAJJ equals or exceeds the material's breaking strength, determined from laboratory tests or calibrated benchmarks.

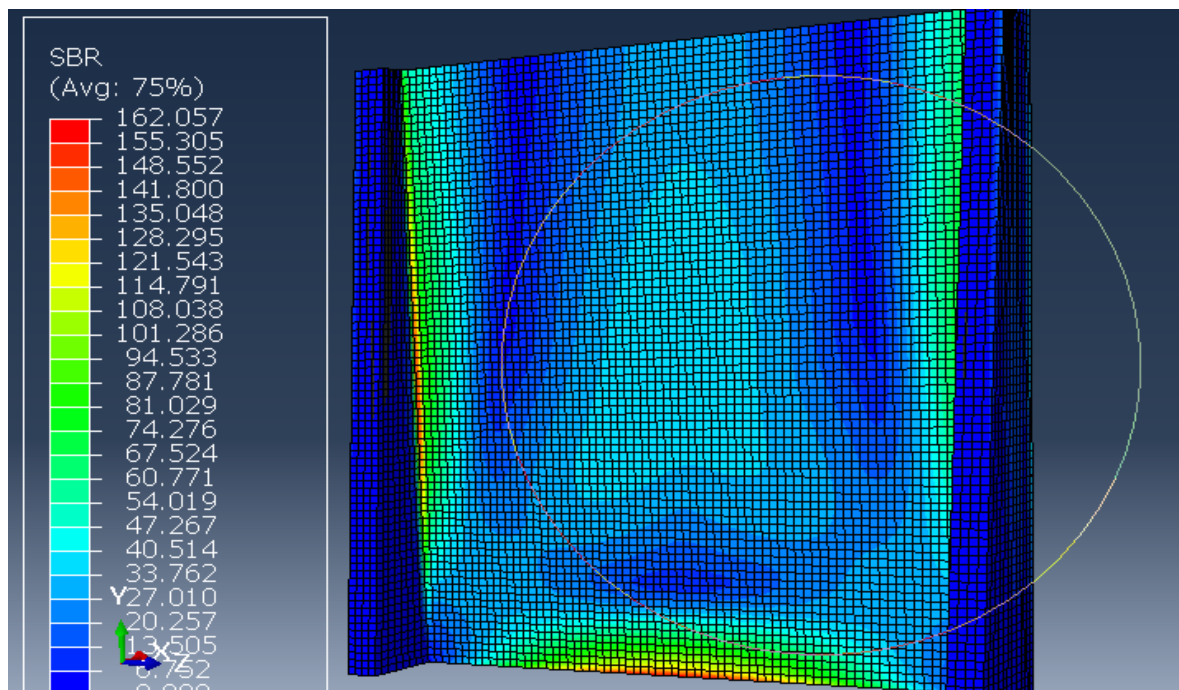


Figure 2. Results: The breaking Stress Distribution for The Considered Dam

Interpretation of Results

Assuming that the maximum breaking strength is 160 MPa, failure is expected to occur at the bottom or at the edges of the dam at a maximum surface applied pressure of 1.5 MPa as shown in Figure 2.

Simulations demonstrated that boundary conditions critically influence stress distribution and failure location. This confirms that realistic boundary modeling is essential for accurate failure prediction—an insight often neglected in traditional analysis relying on Saint-Venant's principle.

The breaking stress criterion successfully captured the relationship between externally applied forces and internally developed stress states. Unlike von Mises or Tresca criteria, which may misrepresent hydrostatic or triaxial conditions, the breaking stress provided a unified scalar measure of failure potential. This enabled precise identification of service-limit capacity across varied material types and structural configurations.

The methodology reveals how boundary conditions influence stress concentration zones and failure locations—insights often overlooked in traditional analysis. The Breaking Stress Criterion enables a more accurate prediction of service-limit structural capacity, offering engineers a robust tool for designing resilient and unconventional dam systems.

Implications for Dam Engineering

The study highlights the Breaking Stress Criterion as a versatile and reliable framework for assessing dam performance. Its seamless integration with finite-element modeling and its capacity to handle complex boundary conditions position it as a valuable tool for contemporary dam design. By incorporating this approach, engineers can enhance safety, resilience, and cost-effectiveness—particularly when addressing unconventional materials or nontraditional structural geometries.

Advancing Material Failure Analysis

Elasticity theory has long provided the foundation for understanding material deformation, yet it has lacked a complementary framework for predicting failure. The Breaking Stress Criterion bridges this gap, offering a unified, physically consistent theory applicable to isotropic, homogeneous, and noncompressible materials. This development signals a turning point: the discipline

can now move beyond theoretical debates toward practical application and systematic validation.

Strategic Directions for Future Work

Progress in this area requires several key initiatives:

Software integration: Commercial finite-element platforms should evolve to include breaking stress as a direct output variable, enabling engineers to track failure potential within simulations.

Application catalog: A structured repository of case studies should be developed, extending the criterion's use across civil infrastructure, aerospace, mechanical systems, and geotechnical engineering.

Experimental validation: Controlled multiaxial testing programs are essential to benchmark predicted thresholds against observed material behavior, strengthening confidence in the theory and refining its scope.

Beyond elasticity: New formulations must capture post-failure processes such as damage progression, plasticity, and fracture mechanics, ensuring a comprehensive description of material behavior throughout a structure's lifecycle.

Reimagining Education and Practice

Equally transformative is the need to reshape how material failure is taught. Current curricula often emphasize empirical rules and fragmented models. Embedding the Breaking Stress Criterion within a unified framework of failure mechanics will equip future engineers with deeper understanding and greater confidence in design.

Toward a Collective Transformation

This shift is already underway. It will be propelled by the combined efforts of researchers, practitioners, and educators who recognize the importance of a coherent, predictive approach to material failure. The most rigorous contributions will not only stand the test of time but also serve as the foundation for safer, more sustainable, and innovative structural design in the decades ahead.

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