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EVOLUTION OF GRIFFITH'S CONCEPT FROM 1921 TO THE PRESENT

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Abstract

This presentation will briefly review the history of the development of fracture mechanics from 1921 to the present, including the evolution of its basic concept. Arguments will be made that Griffith's basic concept, properly implemented in the context of modern non-equilibrium thermodynamics, remains valid.

1. Introduction

The problem of limited service-lifetime and rupture of engineering components became systematically addressed by engineers and scientists during the middle third of the 19th century. In the early 1840s Rankine was working on fatigue problems of railway axles. In the early 1850s, Morin applied an early version of the '*safe-life design approach*' to the estimation of the service life of horse-powered mail coach axes of the time. Wöhler's studies between 1850 and 1870 laid the foundations for a methodology of systematic fatigue tests with scientific requirements. His problem was that components, correctly dimensioned for static loading, often failed during use due to sudden fast fracture, causing accidents.

Engineering history is littered with dramatic examples of disasters caused by fast fracture of large structures, resulting also in significant human casualties. These include the sinking of the Titanic on 15 April 1912 and the series of Liberty-type shipwrecks in the early 1940s, all of which occurred at low temperatures. In Hungary, a catastrophic accident at a carbonic acid processing plant on 2 January 1969, when the weather was particularly cold. In Genoa, Italy, on 14 August 2018, a section of the Viadotto Polcevera (part of a busy motorway heading towards France) collapsed and fell into the valley below. The disaster resulted in 43 deaths and significant material damage. One of the main causes of these accidents was that they were either prone to brittle fracture after manufacture or had become brittle due to the ageing processes accompanying their operation.

2. Results

In continuum-based fatigue strength calculations, the criterion of rupture is based on the following hypotheses: rupture may be expected if: (1) the maximum tensile stress or (2) the maximum strain exceeds a certain corresponding critical value.

During the early 1910s, it was demonstrated experimentally that fatigue test results were strongly influenced by the specimen surface quality. **Griffith**, relying on **Inglis's** theory, realized that to understand the phenomenon, it is necessary to consider the influence of the surface, whether it is surface of notches, or surface of cracks embedded in the material. Griffith's pioneering innovation was to replace the strength-based failure criterion with an energy-based criterion that considered the effect of crack-like defects in the structural material. Although the Griffith's model in its original form fits very well with experiments only for highly brittle materials, such as glasses, the generalization with a small plastic correction introduced by **Orowan** and **Irwin** in 1948, and the generalization allowing arbitrary dissipative phenomena around the crack introduced by **Chen and Mai** in 2013, proved that Griffith's basic concept is essentially valid under much more general conditions than many had for a long time believed. Therefore, 100 years after the original publication, it can still be said that Griffith introduced a new paradigm for the description of the stability and rupture of solids, which –although incomplete– is still fundamentally valid and relevant today.

Griffith's failure criterion was independently modified in 1948 by **Orowan** and **Irwin** so that local dissipation in a small environment around the crack edge is considered. This model was developed further by Irwin in the mid-1950s, when he simplified the problem of defining the stress field around the crack edge by using a singular asymptotic stress field decomposition; the coefficients of the first term of the decomposition are the corresponding stress intensity factors (SIFs). This model of fracture mechanics is linear elastic fracture mechanics (LEFM), which is widely used in standards-based engineering calculations. However, LEFM is well known to be unable to deal with the constraint effects, the microstructure, and the general time-dependent loads on the crack stability due to the inherent limitations of the mathematical approximation used. To address this problem, various micromechanics-based models were developed in the first half of the 1980s, such as the Beremin model, which has since been significantly improved by several researchers worldwide (e.g., **Ruggieri**, **Bordet**, **Siegele et al.**, **Margolin et al.**, etc.). Micromechanics-based models can address many fundamental questions, but their thermodynamic consistency is not always apparent.

A seminal work in the development of fracture mechanics is **Eshelby's** 1951 paper '*The Force on an Elastic Singularity*', which, like Griffith's concept, also relies on energetic considerations. Eshelby was primarily interested in the description of inhomogeneous and microstructured materials. Eshelby's approach is the basis for the *J*-integral developed by **Cherepanov** and **Rice** that is widely used in industrial settings. Eshelby's approach has been developed and extended in the theory of *Configurational Forces* (e.g., by **G. Maugin**, **P. Steinmann**, etc.). Configurational Forces are the thermodynamic driving forces responsible for the dissipation of a structural material during configurational changes; dissipation is governed by the 2nd law of thermodynamics. The theory is by no means closed. In its present form, it is considered more advanced than purely mechanics-based theories as it introduces a thermodynamic perspective into the discussion and is therefore thermodynamically consistent.

Nowadays, models based on *phase field* theories, which we call the third development trend, are becoming increasingly popular in fracture mechanics. The phase field models are derived from the **Ginzburg-Landau** functional describing the corresponding free energy of the system, using variational method; they are widely used to describe the time evolution of phase transitions, microstructures, cracks, and to solve stability problems. In these models, thermodynamic consistency is not automatically satisfied; it must be ensured by special conditions.

The fourth development branch of fracture mechanics is the *Thermodynamic approach*, which emerged in the early 1960s and systematically builds on modern thermodynamics as a framework from the beginning, so that the thermodynamic consistency of the models is inherently fulfilled. The Thermodynamic approach was used to develop the first models describing the fracture mechanics behavior of rheological materials (e.g., **Schapery**, **Mc Meeking** et al.). The Thermodynamic approach was applied by **Chen and Mai** in their 2013 book '*Fracture Mechanics of Electromagnetic Materials*', where they generalized Griffith's criterion to incorporate any form of dissipation. The framework outlined by Chen and Mai is based on the classical theory of irreversible processes, and as such is suitable for describing fracture mechanics of dissipative materials, even in the presence of other –e.g., electromagnetic, chemical– interactions, and can consistently describe ageing processes in a thermodynamic way.

In view of the progress directions in fracture mechanics presented above, the most promising direction for the future seems to be one that is strongly based on the fundamental laws of thermodynamics. Only a holistic theory, such as modern thermodynamics, can be expected to describe the ageing of materials, the initially slow crack growth, and the final cleavage fracture in a coherently integrated way. The detailed models are expected to answer fundamental questions and can then hopefully be used to build engineering models.

3. Conclusions

The 100-year history of fracture mechanics indicates that Griffith based his description of the rupture of materials on an energetic approach that –although incomplete– is still valid today. The key to the further development of fracture mechanics is the incorporation of ***Griffith's concept*** into the context of ***modern nonequilibrium thermodynamics***, in accordance with its fundamental principles.

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