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Fracture mechanics – An interpretive technical history

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ABSTRACT

In this paper, the historical context of the development of what is now known as 'Fracture Mechanics' is selectively developed. We start from the safety and economic motivations, and review the essential efforts, over the centuries, to develop the ability to predict fracture and those factors leading up to final catastrophic events. The experimental and analytical quantitative aspects, and their interdependence, are emphasized. It is shown how these efforts were integrated to define the field we now know as Fracture Mechanics. The paper concludes with some thoughts on unmet needs and new directions.

1. Overview and scope

The occurrence of premature fracture has long been a major and perplexing problem in all structures that must bear a load and many approaches have been adopted to ensure against this phenomenon. The earliest known documentation of the importance of this problem was contained in the Code of Hammurabi [1], circa 1754 BC, and enacted by Hammurabi, the sixth king of the First Babylonian Dynasty, reigning from 1792 BC to 1750 BC. As part of the code, some provisions were devoted to avoiding collapse of buildings through a rather punitive approach:

229 If a builder build a house for someone, and does not construct it properly, and the house which he built fall in and kill its owner, then that builder shall be put to death.

230. If it kill the son of the owner the son of that builder shall be put to death.

231. If it kill a slave of the owner, then he shall pay slave for slave to the owner of the house.

232. If it ruin goods, he shall make compensation for all that has been ruined, and inasmuch as he did not construct properly this house which he built and it fell, he shall re-erect the house from his own means.

233. If a builder build a house for someone, even though he has not yet completed it; if then the walls seem toppling, the builder must make the walls solid from his own means.

Clearly these provisions do not provide any objective standards by which failure could be avoided and just as clearly encourage gross overdesign, c.f. provisions 229 and 230. As society evolved, better materials and more means became available to design against failure. An example of this is found in the work of Albert [2] circa 1838, who showed that repeated load application on a mining chain would cause failure at lower loads than expected. This process was termed "fatigue" by Poncelet [3] in the second published edition of his book on mechanics in 1839. It contains lecture notes and other writings on mechanics and shows that he was using the term "fatigue" in his lectures at the Sorbonne. Perhaps the best-known systematic early studies of fatigue were carried out by Wöhler [4,5] in Germany in response to severe accidents in Prussian railways caused by failure of the rails after many "cycles" had been applied by the trains. Wöhler devised an experimental rotary bending fatigue machine and was able to determine the stress amplitude at which the life of the rail steel he was testing would be "infinite". It is noteworthy that eighteen years before Wöhler's earliest published work, in an investigation of the disastrous Verdun train crash in France, Rankine of thermodynamic renown, showed that the failure origin was in an axle journal at a location where there was a very sharp angle [6]. He pointed out that the accident was caused by fatigue which initiated at the stress concentration at the sharp angle and propagated from the surface to the interior. He also debunked the then-current notion that failure was caused by "crystallization" and recommended reducing the stress concentration by machining in generous radii. This recommendation is now considered to be good engineering practice and when ignored, as we shall see, has led to disaster. While these recommendations were very useful, they are essentially qualitative. It was becoming increasingly clear that

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the ability to predict the onset of fracture needed to be put on a quantitative basis. It was recognized that the ability to absorb energy was a key property for a material to have fracture resistance. This means that not only is strength important in load bearing applications, but so too is the ability of a material to deform without breaking. The plastic deformation behavior of a material was thus understood to be important. While the basic physics of deformation was not at all understood, qualitative differences in macroscopic behavior were obvious. Considère was able to calculate that for materials which follow simple power law hardening, the onset of plastic instability, a form of failure, took place when the true strain was numerically equal to the power law exponent (i.e. the so-called strain hardening exponent). This approach actually provided a quantitative prediction of failure and also provided guidance for material selection. However, given the severe conditions to which structural components were subjected such as low temperatures, high rates of loading and notches, some way of taking these conditions into account was needed. Recognizing that practical complexity, Charpy developed what is now known as the Charpy V-Notch Impact Test or simply the Charpy test around 1901 [7,8]. The notch, high testing rate and low possible test temperatures all suppress plasticity and favor low energy (brittle) fracture. This test was a very important contribution to appropriately screening materials but could not be used to analytically predict the conditions (i.e. loads, crack lengths etc.) under which fracture takes place. Nevertheless, this was a very important contribution to the fracture control problem and is widely used to this day, especially in material comparison and selection. However, a more quantitative approach was needed in order to make reliable predictions. About a decade after Charpy's seminal contribution, a very important analytical advance was made. Using advanced mathematical and mechanics techniques, Inglis [9] calculated the stress at the tip of an elliptical notch in a body subjected to a specified remote load.[1] Inglis' result was an important step forward since it allowed designers to introduce simple stress based criteria in an effort to avoid fracture. For example, an extremely simple criterion would be to limit the remotely applied stress so as to maintain the stress at the tip of an elliptical notch below yield, then chances of early failure would be limited. Of course, that is true, but the problem is that one does not always know notches are elliptical nor, as a practical matter, can this be determined. One only has to consider weld cracks and cracks due to rivets to see the practical limitations of Inglis' approach. Just about one decade later, Griffith [10] carried out an analysis for actual cracks and developed an expression for the remote stress that would cause fracture of a part containing a crack-type defect of a given size in a given material. Griffith's analysis was limited to a through-crack of length $2a$ in a linear elastic, isotropic, homogeneous material subject to uniform stress in a direction normal to the crack faces. While it did provide an analytical criterion for the onset of fracture in a given material, it was still quite geometrically limited and did not take into account any plastic deformation that might occur around the tip of the crack. This latter limitation was removed by Orowan [11] who proposed that the formation of new surfaces during fracture is accompanied by plastic deformation in metals, an energy absorbing phenomenon much like surface energy for new surfaces. Therefore, a plasticity-related adjustment in the material's surface energy (i.e. effective increase in surface energy) allowed the form of the Griffith equation to be maintained in engineering calculations.[2]

In the early 1960s, with the development of the discipline that we now call "Fracture Mechanics" and as discussed in the main body of the paper, Irwin examined crack-tip plasticity in detail [12]. He was able to demonstrate that the size and shape of the plastic zone around the crack tip may be described by the stress intensity parameter K, the key parameter in linear elastic fracture mechanics (LEFM). The mathematical foundation of Irwin's proposal of K as the amplitude of the crack tip stress field was derived from the work of Westergaard [13] who was successful in deriving the approximate crack tip stress field in front of the crack in a region in which the first singular term of a power series dominates. If the fracture processes occur primarily in this region, K should uniquely predict fracture.

While the work on developing a predictive methodology proceeded, fatigue studies lagged behind. Fatigue continued to be handled by what is essentially the Wöhler approach in which an S/N (stress vs cycles) curve was developed and operating stresses were set as the stress that would not cause failure earlier than a predetermined life. When dealing with steels those stresses were generally set at the so-called "fatigue or endurance" limit which is the stress, below which fatigue failure will not occur. Some advances were made in dealing with mean stresses but these were generally based on the simple notion that increases in the mean stress meant that the stress amplitude would have to be reduced according to some essentially empirical rule. The Goodman [14] and Gerber [15] approaches are typical of these methodologies. In these methodologies, the crack initiation and crack propagation phases were generally not distinguished. Thus, certain ambiguities and sources of dispersion of experimental results were not resolved. It was not until 1961, when Paris et al. [16] applied the new discipline of Fracture Mechanics to crack propagation, was it possible to predict the fatigue crack propagation life.

The developments which were briefly mentioned in the preceding paragraphs were useful in their times and as far as they went. However, they all either lacked any quantitative predictive capability or were very limited in terms of material and geometry. A general quantitative methodology that could be applied to monotonic loading, fatigue and to environmental effects was clearly desirable. In essence, an approach that allowed the rate of cracking and the final failure conditions to be computed was essential in putting prediction and control of fracture on a firm foundation. The methodology that evolved has come to be called "Fracture Mechanics" and was the result of interdisciplinary work and synthesis in mechanics, mathematics and materials science over many decades.

Fracture Mechanics, the subject of this historical review, may be defined, as the science of predicting fracture loads, critical crack lengths and the rate at which cracks grow to critical length in air and other environments. Its practical application requires:

- Experimental measurements of material behavior (static, dynamic, cyclic loading).
- A detailed knowledge of the load/crack geometry and other external variables such as environment and temperature.
- The loads to which the component is subjected.
- An analytic criterion for that combination of loads and crack lengths that gives rise to failure for a given material and load/crack geometry.
- The ability to reliably and accurately determine crack size and shape.

[1] Actually, Inglis calculated the stress *everywhere* in the body but the complexity of the result and the lack of digital computers severely limited the ability to exploit the completeness of Inglis' results.

[2] Griffith recognized the practical limitations of his approach when working with metals. In his seminal article, he noted "*"In the case of plastic crystals, we are further hindered by the fact that rupture is almost invariably preceded by plastic flow, whose nature is still the subject of hot controversy. In fact, it may be said that, at the present day, there is no theory of the rupture of such solids, insomuch that no attempt has been made to cope with the basic problem, namely, the discovery of the source of the surface energy of the cracks."*