The Historical Development of Our Understanding of Fracture

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Editor's Note: The following is a distillation of George R. Irwin's presentation at the McClintock Luncheon, held in Orlando, Florida, during the 1997 TMS Annual Meeting. The historical material in this paper was first reviewed in a paper by G.R. Irwin and A.A. Wells in *Metallurgical Reviews*, 10 (38) (1965). The George R. Irwin Symposium on Cleavage Fracture: Theory, Experimentation, and Modeling is being held in Dr. Irwin's honor at Materials Week '97, September 14–18, 1997, in Indianapolis, Indiana.

Investigations of fracture prior to the advent of fracture mechanics are interesting and can improve the perspective with which we view current fracture problems. In addition, it is natural to wonder how engineers coped with fracture strength limitations in previous centuries and what events stimulated development of fracture mechanics techniques. In this article, historical completeness is not attempted, particularly with regard to the oldest part of the story. The matters presented were selected mainly for illustrative value.

INTRODUCTION

Fracture events are most typically unexpected, sudden, and unfortunate. When such an event occurs, it is natural to center attention on minimizing the undesired consequences. A careful understanding of sudden and rather complex fracture behaviors in terms of separational mechanisms may seem to be relatively unimportant, however, these details need to be understood for practical reasons. With technological progress, we have become increasingly dependent upon structural reliability. The confidence with which fracture reliability can be achieved depends very much upon an understanding of how and why fractures occur and upon proper use of this information in design, fabrication, quality control, and the establishment of safe operational conditions.

Upon reflection, it can be understood that structural components may contain a wide range of local weaknesses. For simplicity, these will be termed flaws. Sometimes cracks are introduced by forging, welding, or heat treatment. At fine scale, there may be poorly bonded inclusions or grain boundaries weakened by impurities. Quality control can reduce, but not eliminate, flaws. In addition, the local stresses may differ substantially from the average stress across a section of the component. A structural fracture begins naturally at a position where the combination of local weakness and local stress is most severe. Given that a crack forms across such a region or given an initial fabrication crack, the structure may be safe or unsafe relative to rapid separation depending upon what can be expected in terms of progressive crack-extension behavior. Obviously, the severity of a prior crack or a local flaw-stress combination is somewhat a matter of chance, and a statistical viewpoint can assist the understanding and use of fracture behavior information. However, it is also clear that progressive spreading of an initial crack is the feature of main importance to a structural fracture failure. Probabilistic aspects of fracture mechanics is an emerging field of study that can succeed only when based upon a sound understanding of crack-extension behaviors. In this article, statistical viewpoints rarely will be used. Instead, attention will be centered upon crack-extension behaviors in terms of the progressive separation viewpoint.

There were essentially three time periods in the history of fracture. During the first period, the principles of similitude were developed, and the individual importance of flaws was ignored. During the second period, fracture size effects were explored, mainly with notched bar testing. Following 1945, serious fracture failures coupled with the rapid pace of technological development resulted in the development of fracture mechanics and fracture control plans.

THE NATURE OF FRACTURE

The application of stress analysis methods is expected to reveal regions of very high stress near the leading edge or front of a crack in a solid. We are concerned primarily with the response in terms of crack extension within this overstressed region. Relatively simple methods can be used to characterize the stress-strain state surrounding the region that contains the progressive crack-extension process. This finding greatly simplifies model studies of progressive fracturing. It means that a model study of a crack in a service component may not need to duplicate the size and geometry of the component. Given the similarity of material in the component and in the laboratory test specimen, it can be assumed that the crack extension in the component will be like the observed crack extension in the test specimen when the characterization parameters pertaining to the stress-strain field local to the crack front are similar. This macroscopic viewpoint is basic to measurements and applications pertaining to fracture toughness, fatigue and stress corrosion cracking, and corrosion fatigue.

The mechanisms of fracturing at a fine scale are complex and vary widely in nature in different materials. In certain situations (e.g., the cleavage fracturing of structural steel), aspects of fine-scale fracture behavior influence the interpretation of test results and, therefore, must be considered. In general, the current understanding of fracturing at a fine scale is incomplete. The macroscopic-behavior viewpoint must come first, both for practical reasons and as an aid to better understanding of the mechanisms of separations at fine scale.

From an essentially academic viewpoint, the progressive fracturing of a solid is a mechanical behavior of unusual interest. The analytical aspects are simple enough in certain cases and sufficiently complex in others to attract a wide range of applied mathematics interests. Experimental fracture mechanics may be done with commonly used devices for measuring load and displacement. Other aspects (e.g., dynamic fracturing) can be assisted by the use of modern photomechanics techniques. Furthermore, the entire subject of fracture mechanics is sufficiently young so that much remains to be explored and discovered.

THE EARLY UNDERSTANDING OF FRACTURE

The Earliest Studies

One of the earliest recorded examples of fracture strength testing reflected a strong influence of specific flaws. One of Leonardi da Vinci's sketch books[1] shows a drawing of an apparatus for testing the strength of various lengths of iron wire. From our knowledge of how iron wire was produced in 1500, da Vinci's results were plausible and realistic.

Nearly one century later, Galileo taught that the strength of a column in compression or tension would depend only on the section area, not upon length.[2] In this instance, Galileo's viewpoint was analytical. From this viewpoint, it is natural and convenient to ignore individual flaws and to regard every unit area of a cross section as capable of the same strength. Galileo, like many subsequent engineers and scientists, preferred to express the idealizations of his mind in analytical form.

About 1650, Louis XIV of France determined to build a palace and grounds at Versailles that would possess unusual grandeur. Grandeur implied fountains of great height, and this implied containment of substantial amounts of pressurized water. The engineer, Mariotte, designed a method for bringing water to Versailles from the Seine River above Paris with enough pressure to supply the fountains. Mariotte's tests of deformation and burst pressure of trial cylindrical vessels were reported in some detail to the French Academy of Science.[3] He reported that the vessels appeared to burst when the fractional increase of circumference reached a critical value. Before the publication of Hooke's Law (of which Mariotte was not aware), the engineer reported the close proportionality between pressure in his test vessel and the circumferential stretch. Mariotte's statement of a strength law based upon critical strain was the first of a number of research efforts to express strength in terms of stress-strain relationships.

The 1800s

As continuum mechanics developed during the next two centuries, methods for expressing strength laws in general form were explored. The graphical method introduced by Mohr about 1860 contained as much generality as was achieved 100 years later when the use of tensor notation became fashionable. The analytical viewpoint was dominant, and laws of similitude seemed to be firmly established.

About 1830, two sets of experimental results were reported.[3] Lloyd tested the tensile strength of various lengths of iron rod, and Le Blanc studied the influence of specimen length on iron-wire strength. In both cases, the average strength decreased with an increase in length of the test specimen. The observed size effects were relatively small and were ascribed to the presence of nonuniformities. These results were reported long before statistical methods were developed that might have been applied to their analytical treatment. In fact, 100 years elapsed before Weibull converted available methods of extreme value statistics into a worst-flaw statistical theory of fracture strength.

Love's *Treatise on the Mathematical Theory of Elasticity* (1892) contains a brief chapter on hypotheses concerning safety. The section, which discusses fracture, states that "the conditions of rupture are but vaguely understood." According to Love, it was common practice for English and American engineers to require that the largest tension in the structure should be some fraction of the breaking stress as determined by tensile tests. The denominator of this fraction, termed factor of safety, was 6 for boilers and axles, 6–10 for railway bridges, and 12 for propeller shafts. However, the analysis accuracy of the mathematical methods discussed in the book was regarded as adequate so long as stresses remained below the yield strength of the material. Obviously, the large safety factors that were in common use were based on practical experience rather than theoretical analysis, and it was the reasons for these safety factors that were vaguely understood. Large testing machines such as that used for testing iron bars by Lloyd were coming into use, and engineers tried to supplement failure experience with laboratory testing.

The introduction of Krupp composition alloy steel for ordinance applications around 1860 was followed by the development of notched-bar impact testing. As is well known, this steel can be embrittled by slow cooling from the tempering temperature. The presence of this undesirable condition was most conveniently revealed by impact tests of notched bars.

The Early 1900s

In 1909, Ludwik[4] explained the relatively abrupt increase of notched-bar fracture work with an increase of test temperature. He assumed there was a cohesive strength, nearly independent of temperature, and a yield strength that decreased with temperature. Elevation of the test temperature to the point where the yield strength was less than the cohesive strength resulted in substantial plastic strain prior to fracture. From the Ludwik theory, the fracture work remained small below a critical temperature and increased rapidly when this temperature was exceeded.

The Ludwik explanation was phrased in stress-strain terms from which one could infer that laws of similitude would apply. However, in 1920, Stanton and Batson[5] reported that similitude did not apply to impact fractures of notched bars of structural steel. The temperature of brittle-ductile transition could be increased by increasing the test bar size, and the fracture work per unit volume decreased with a scaled increase of test-bar dimensions. During the 1930s, Docherty conducted similar notched-bar tests in bending with slow loading to eliminate dynamic uncertainties inherent in the tests by Stanton and Batson. Again, the existence of large fracture size effects was evident. After witnessing one of Docherty's spectacular fracture-size-effect demonstrations, an editor of the British journal *Engineering* wrote a description of the demonstration test,[6] in which he commented that the principles of mechanical similitude appeared to be overthrown where cracking occurs. He observed that similar size effects had been demonstrated in fatigue testing of notched bars. At this time, it was well known that the safety factors customarily used in design depended considerably upon judgment estimates of the possibilities of fracture. Nevertheless, no perceptible influence of the Stanton-Batson and Docherty results on design details occurred. There was an awakening of interest in improving design details that was stimulated by Neuber's 1937 book[7] on stress analysis of notches, but this was not associated with fracture-size effects in technical discussions.

MODERN FRACTURE MECHANICS

Before 1960

The basic ideas leading to the start of modern fracture mechanics can be related to a theory of the fracture strength of glass published by A.A. Griffith in 1920 and to the introduction of dislocation mechanics. The Griffith theory[8] assumed that fracture strength was limited by the existence of initial cracks. An applied tensile stress of critical size for unstable extension of the largest initial crack was calculated by equating the stress-field energy disappearance rate to the increase rate of surface energy per increment of crack extension. An agreement was claimed between theory and experiments using precracked glass bulbs. Now, this agreement appears to have been coincidental. Clearly the assumption of perfect energy transfer efficiency from stress-field energy to surface-tension energy was both naive and impractical. In glassy solids and particularly in structural metals, separational mechanisms involve so much energy loss into nonelastic strains that the resistance to crack extension is scarcely influenced by the solid-state surface energy.

The development of crystalline dislocation mechanics during the 1930s to 1950s furnished important ideas that were directly transferable to fracturing. The alignments of lattice faults, termed dislocations, provided an answer to the plastic-flow weakness of metal single crystals. Simple estimates showed that rigid shear displacement across a slip plane would encounter a resistance on the order of one-tenth of the shear modulus. However, from the viewpoint of dislocation mechanics, the stress necessary to loosen bonds across the slip plane is provided locally by the dislocation irregularity in the metal lattice. The relatively easy glide of dislocations across slip planes in response to applied shear stress results in adequately low estimates of resistance to plastic flow. In structural metals, interference in the easy glide of dislocations occurs because of internal complexities such as grain boundaries and minute inclusions. Although the resistance of metals to plastic deformation is generally understood, the details are quite complex, and strength is normally determined by measurement rather than by computation.

Similar considerations are directly applicable to fracturing. Historically, structural fractures that were vaguely understood were those that occurred when the applied stress was substantially less than the yield strength of the structural material. If separation is assumed to occur simultaneously everywhere on the plane of separation, then the applied stress necessary for separation cannot be less than the ultimate tensile strength and is probably larger. However, given the presence of an initial crack, the natural stress concentration influence of the crack produces very large stresses near the leading edge or front of the crack. If these local stresses are large enough to cause progressive fracturing, then complete separation may occur at an applied stress that is much less than the yield strength of the material.

In dislocation mechanics, it can be shown that the stress-field force driving a dislocation is the product of the Burgers vector times the parallel component of applied shear stress. In the force derivation method, the force is computed as the derivative of the (system-isolated) stress-field energy per increment of forward motion of the dislocation line. A knowledge of the deformation details within the core of the dislocation is not required. Assuming that nonelastic strains along the crack front are well enclosed by an elastic stress field, the same generalized force concept can be applied to the leading edge of a crack. If the force is computed per unit of length along the disturbance zone (the crack front) in a manner similar to the dislocation line force, the result has the same dimension, force/length. In fact, the Griffith crack theory is obtained if the crack extension force is equated to twice the solid-state surface energy of the material. However, the deformation details that provide resistance to crack extension are even more complex than those that provide resistance to plastic straining. Thus, critical values of crack-extension force necessary for various kinds of actual crack extension must be determined by experimental measurements. Although the Griffith crack theory had suggestive value, the influence of dislocation mechanics upon the development of modern fracture mechanics was direct and more persuasive.

Beginning in 1937, investigations on armor were conducted at the U.S. Naval Research Laboratory to assist the solution of brittle fracture problems in heavy armor and to explore the feasibility of light armor for aircraft. Although the brittleness problems with heavy armor were resolved early by metallurgical techniques, the critical influence of fracture strength upon armor quality, the evidence of fracture size effects, and the obvious lack of understanding of fracture encouraged additional study. This interest resulted in a research contract for studies of fracture at the University of North Carolina between 1941 and 1948. Although the reported results of fracture-size effects[9] were of interest, the main practical value was the perspective provided by a thorough review of previous fracture investigations. Program revisions related to the ending of World War II then permitted the settlement of plans for a new research program based upon the progressive crack extension viewpoint.

At the outset, it was clear that the new viewpoint would provide at least a partial explanation for fracture-size effects. The notched-bar fracture size effect observations indicated that the energy associated with fracture varied with specimen size in a manner intermediate between proportionality to specimen volume and proportionality to severed area. Naive interpretations of the progressive-fracturing viewpoint suggested that a direct proportionality of fracture work to severed area would be ideal. But, the experiments contained interpretation problems, and study of dislocation mechanics provided strong support for the new fracture research plan.

The ideas basic to linear-elastic fracture mechanics were suggested in a 1948 paper by Irwin[10] and were presented more firmly in unrefined but useful form in 1952 and 1954 papers by Irwin and Kies.[11,12] There were three fundamental ideas presented. First, attention should center on the progressive-forward motion of the crack front (leading edge or crack tip). Second, the crack-extension force, G, was the rate of loss of stress-field energy at the crack front per increment of crack extension. Third, the resistance to crack extension was the rate of energy dissipation into nonelastic strains close to the crack front.

Initial trials conducted using metallic sheet materials, plastics, and glass provided entirely favorable results. The prospects for practical applications to brittle fracturing were enhanced by the recognition that the energy loss per increment of severed area, G, depended only on the stress-strain field surrounding the limited zone of nonlinear strains at the crack tip. Thus, knowledge from prior measurements of the critical value of G for crack propagation, G_c, furnished a one-parameter criterion that could be used to predict the critical load for propagation of a prior crack of given size and location in a service component. The Irwin-Kies papers provided an experimental method for the determination of G, which is usually termed compliance calibration.

The first successful practical application of the research was associated with the development of stretch-toughened glazing materials for aircraft in 1953-1956. Additionally, it was noted that the fractures of the welded Liberty ships, bursts of several large petroleum storage tanks, and the pressurized cabin fractures of the DeHavilland Comet jet airplanes all seemed understandable in terms of this new fracture-strength viewpoint. The explanatory method was relatively simple. A value of G_c was estimated from laboratory tests of precracked specimens. Using appropriate stress analysis methods, the value of the driving force G that tended to extend the starting crack revealed by fracture failure examinations was computed. In all cases, the comparison showed that the toughness had not been large enough to prevent crack propagation.

The introduction of prior cracks or defects that generate cracks soon after tensile loading can occur in many ways during the fabrication of structures, particularly welded structures. It is now understood that welded structures such as bridges and pressure vessels have commonly provided many years of faithful service despite the presence of such defects. However, this was not an accepted understanding during the early development period of fracture mechanics. Most engineers preferred to take at face value the "no cracks" clause usually included in specifications. On the other hand, the possibilities for planning fracture safety in a sure way required the recognition that overlooked defects of finite size may be unavoidable in welded structures.

It was necessary to overcome a substantial amount of unsympathetic reaction. At the same time, the analytical and testing techniques of fracture mechanics needed improvement. Both of these objectives were sufficiently achieved by 1960 so as to guarantee acceptance and continued growth of fracture mechanics technology. Primarily, three major fracture problems were responsible—the DeHavilland Comet fractures, fractures of heavy rotating components of large steam turbine electric generators, and fractures of Polaris and Minuteman solid-propellant rocket chambers. In all of these, the fracture problem was related to the use of a relatively new higher strength metal. More importantly, the penalties for failure to solve each of these problems in a timely way were unacceptable. Fracture mechanics assisted in the solution of these problems. In return, each of these applications made significant contributions in terms of new fracture behavior information, analysis methods, and testing techniques.

The 1960s

In January 1960, a special committee of the American Society for Testing and Materials (now Committee E-24 for the fracture testing of metals) reported[13] that fracture mechanics could be used to determine whether a fracture test is measuring the significant factors governing performance and the degree in which a fracture-test result can be generalized to the more complex structure existing in service. By this time, the U.S. Naval Research Laboratory program on fracture mechanics was only a moderate portion of a national effort. Leadership of this effort through the activities of ASTM

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Committee E-24 has been consistent and quite helpful.

During the 1960–1967 period, the application of fracture mechanics to fatigue and stress-corrosion cracking revitalized these topics both with regard to research and practical fracture control applications. Fracture-mechanics-based research extended into other fields such as the fracture of adhesive joints, composites, rock, ceramics, and glasses. Much of the effort during this period was related to NASA and U.S. Department of Defense aerospace programs. In 1967, a provisional ASTM testing method for plane-strain fracture toughness was nearing completion and was already being used. However, it was clear that a consensus agreement on standard methods of toughness evaluation generally applicable to a wide range of sheet and plate materials required the development of new characterization methods that still retained validity in the presence of relatively large crack-tip plastic zones.

During 1960 to 1968 several ideas emerged,[14] and a number of problem areas suitable for trial of these ideas were at hand. From the applicability of fracture mechanics, the problem areas of most significance were those that did not involve high-strength materials (used primarily in aerospace tasks). For example, reexamination of the fracture safety of pressurized water vessels in nuclear power plants revealed that the possibilities for fracture during rapid internal cooling required additional study. As a second example, it was found that fracture mechanics provided adequate understanding of two major bridge fracture experiences—the King's Bridge at Melbourne (1963) and the Silver Bridge at Pleasant Point, West Virginia (1967). Although currently available fracture mechanics analysis methods assisted in the understanding of these problems, the expansion of practical fracture mechanics technology to include advanced methods of characterization is clearly needed for efficient fracture control during the coming years. This expansion is making progress but is still some distance from completion.

CONCLUSION

The importance of the initiating program at the U.S. Naval Research Laboratory and the 1920 Griffith crack theory should not be overemphasized. The essential analysis ideas were nearly obvious from basic principles and could have received appropriate expression at any time given sufficient motivation. What really happened was that the practice of learning safety factors with the aid of fracture failure experience, a practice which had been in need of enlightened replacement for some years, became too expensive. Innovative progress with materials and structures demanded improved understanding of fracture strength and improved methods for fracture control.

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