Fracture – An Unforgiving Failure Mode

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Keywords: fracture, fatigue

Abstract

During the 2005 Conference for the Advancement for Space Safety, after a typical presentation of safety tools, a Russian in the audience simply asked, "How does that affect the hardware?" Having participated in several International System Safety Conferences, I recalled that most attention is dedicated to safety tools and little, if any, to hardware. The intent of this paper on the hazard of fracture and failure modes associated with fracture is my attempt to draw attention to the grass roots of system safety – improving hardware robustness and resilience.

Introduction

Fracture often results in catastrophic accidents as illustrated in the historical cases in the next section. Brittle fracture seemingly often occurs with little or without warning because the flaws or cracks are often hidden within the structure. This paper summarizes the science or art of fracture mechanics in terms useful to a safety engineer.

Data supporting fracture mechanics is typically published in reports summarizing test of various materials under very specific and controlled test conditions. The activity at the crack tip is where all the action is taking place and is least understood. There are more things or variables contributing to the fracture mechanics than there are equations, so the results of the test data is reduced often through regression analyses techniques to attain equations which can only be applied for a specific material, under the conditions for which the material was tested. There are often patterns but with exceptions for every pattern. The primary factors influencing a structure's resistance to fracture are listed below and discussed in other sections of the text:

- Material toughness
- Crack attributes
- Applied load
- Environment/Temperature
- Material thickness

Historical Lessons

The Silver Bridge spanned over the Ohio River connecting Point Pleasant, West Virgnia, and Kanauga, Ohio. It was constructed in 1928 and consisted of a 700 foot center span and 380 foot side spans. At 5:00 PM on December 15, 1967, the Silver Bridge collapsed claiming 46 lives and injuring 9. The Christmas rush applied an extra load to the 39 year old bridge causing a cleavage fracture in one of the "eyebars". The structure only took about 1 minute to completely fall into the river below. The 700-foot center span, the two 380-foot side spans, and the towers collapsed. In January, 1919, a molasses tank ruptured in Boston spilling 2.3 million gallons of molasses killing 21 people and drowning several horses. The flow crumpled the steel support of an elevated train, and knocked over a fire station. The De Havilland Comet built in Hatfield, Hertfordshire, United Kingdom in 1949 was the first non-military jet. But cracks originating at the square windows resulted in aircraft crashes. In the early 1970's several ships were lost as a result of brittle fracture. Nine T-2 tankers and seven Liberty ships broke in to. In 1966 a NASA rocket motor case failed at 542 psi which was only 56% of intended proof pressure. Crack velocities were estimated of approximately 500 ft/sec. The 65 foot high chamber was .73 inches thick. A competitor built a similar test article constructed of 200 grade steel with 10% lower yield but higher toughness. That rocket motor case had 2 successful proof test and 2 successful firings producing 6 million pounds thrust.

Fracture Mechanics Principles

Recollection of the stress-strain curve from strength of materials is essential to gaining the most basic or elementary understanding of the concept of fracture mechanics. Fracture is the failure of a material in a brittle manner. The first section of the stress-strain curve is linear representing plane strain. Even though this represents an elastic region, under certain conditions ductile material fails in a brittle manner and these failures are often catastrophic. Factors influencing a structure's resistance to fracture are addressed below:

Material Toughness: Rolfe and Barsom define material toughness as, "Material toughness is defined as the ability to carry load or deform plastically in the presence of a notch and can be described in terms of the critical stress-intensity factor under conditions of plane stress or plane strain for slow loading and linear elastic behavior." Simply stated, material toughness is the resistance of a material to crack; or material toughness may be thought of as the resistance of a pre-existing crack in a material to propagate. High strength structural steels with a corresponding high yield value, normally exhibit a lower toughness value than do lower strength structural steels with a lower yield. Again, this is typical behavior, but not absolute. Only testing under the conditions for which the structure is expected to see insures the design can support the assumed loads in the presence of cracks below the size of the assumed threshold.

Crack Attributes: Elimination of all cracks without consideration of the flaw or crack size or elimination of crack causes is impossible since this means elimination of corrosion and vibration for which structures are subjected along with the inappropriately implied assumption that all structural material can be perfectly cast and without stress risers such as holes and welds. Crack size, crack location and crack orientation contribute to probability of structural failure. Fracture mechanics evaluate material based on the following 3 basic crack types, each of which reflects different constants in the fracture mechanics equations:

- Through thickness crack
- Edge crack
- Surface crack

Applied Load: The simplest scenario is when a tensile load is lowly applied to a test article. The test article may or may not have a pre-existing crack. Then a determination is made if a crack formed or the pre-existing crack propagated and if so, by how much. In this manner, the material is allowed time to adjust to the load in a ductile manner. When the load is applied quickly or dropped onto the test article, the test article may or may not have time to yield depending on the material toughness. When cyclic load fatigue is involved the test is complicated further because the result is influenced by both the range within the amplitude and the time elapsed between each cycle. The material must be tested to the anticipated loading that the design is expected to encounter.

Environment/Temperature: Most material attributes change with temperature changes. As temperatures are reduced further and further, a ductile material begins transition to brittle behavior. This estimated temperature is called the Nil-ductility transition temperature (NDT). This is not an exact point on a curve which is a gentle curve, but is an assigned location based on slope change. Because of significant differences in fracture toughness attributes, planning design about the expected service temperature range is essential. Temperature is especially important when working in the extremes such as with Cryogenics (e.g. Hydrogen which boils at -422 F and freezes at -434 F).

Material Thickness: One of the surprises in the study of fracture mechanics is to see a ductile material failing in a brittle manner at a reasonable working temperature. Action in the crack tip is affected by the thickness of the material. A thin sheet of ductile material shows flexibility which the exact same material in a thick plate at the exact same temperature appears stiff. The material in the form of the plate only exhibits the ductile behavior at a thin surface layer. The material in the middle is 'constrained' in a manner such that it behaves in a brittle manner once the crack penetrates below the ductile surface layer. This is the reason why care must be taken when conducting research for published test data to support a future design effort. The material in the test data needs to be thick enough to correspond with the thickness of the material in your design.

Fracture Mechanics Design

The fracture hazard is managed through use of a fracture control plan. In addition to the fracture mechanics principles listed in this report, the plan includes objectives such as leak before burst. The plan should also provide maintenance and service instructions such as coatings to reduce corrosion and inspections techniques for both first time acceptance and follow-on inspections for the life of the structure.

To minimize the probability of failure from brittle fracture, the design engineer has three controllable factors:

- Material toughness at the assumed service temperature and load rate.
- Nominal stress level.
- Flaw size present in the structure.

The design engineer must have established the following general information related to fracture mechanics for all types of structures: Service conditions, and applied stress or stress range for cyclic loadings.

Sources of cracks and crack growth:

- Material voids
- Fatigue
- Stress corrosion

Fracture Control Plans: The safety and reliability of a design is best managed through use of a fracture control plan. Project goals related to fracture such as leak before burst which set design constraints are listed in the fracture control plan. Barsom and Rolfe maintain that a fracture control plan is used:

- "To identify all the factors that may contribute to the fracture of a structural detail or to the failure of the entire structure.

- To assess the contribution of each factor and the synergistic contribution of these factors to the fracture process.

- To determine the relative efficiency and trade-off of various methods to minimize the probability of fracture.

- To assign responsibility for each task that must be undertaken to ensure the safety and reliability of the structure."

Barsom and Rolfe further assert that the fracture control depends on:

- "The fracture toughness of the material at the temperature and loading rate representative of the intended application. The fracture toughness can be modified by changing the material used in the structure.

- The applied stress, loading rate, stress concentration, and stress fluctuation, which can be altered by design changes, loading changes, and by proper detailing.

- The initial size of the discontinuity and the size and shape of the critical crack, which can be controlled by design changes, fabrication, and inspection." Inspection methods along with attributes of each method are listed in Table 1.

TECHNIQUE	FLAW TYPE	STRENGTH	WEAKNESS/LIMITATION
Dye Penetrant	Surface	Inexpensive, reliable Best method for detecting surface cracks on nonmagnetic material	Must be completely removed before subsequent passes on multipass welds because the penetrants may break down
Radiography	all	Show flaw size and orientation	Expensive and slow Does not detect oxide films whose density is similar to the weld A rough surface obscures flaws A tight crack in a plane parallel to lines of x-ray not detectable Does not detect fatigue cracks less than 1% of material
Mag Particle	Surface thru 1/8" below surface	Effective detecting root slag, or excessive porosity on root passes	Material must be magnetic Unsatisfactory for joints between metals with dissimilar magnetic characteristics
Ultrasonic	All	Inexpensive, fast	Difficult to interpret results
Eddie current	Surface or near surface	Only method to detect bolt hole defects	Material must be conductive Accuracy reduced when used on magnetic material Slow

Table 1
Non Destructive Test Methods Sample

Summary

This paper only provides the system safety engineer with the basics associated with the hazard – fracture. The next level of understanding is accomplished with a terse review of graphs and equations available in the reference below.

The use of protective coatings to prevent corrosion which is a primary tool preventing one source of crack initiation is outside the scope of this course. The American Society of Corrosion Engineers is one source for both inspectors and training in this area.

Reference

Barsom, John, and Rolfe, Stanley, Fracture and Fatigue Control in Structures, 3rd Edition, Butterworth-Heinemann Publications, 1999, pages 15, 23-24.

Biography

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Ronnie Goodin has 31 years of system safety and industrial safety engineering experience with both DOD and NASA.

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4 years in Shuttle Program Safety

2 year safety support of Engineering Development (Current)