Fracture Considerations for Surveillance Programs

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The structural capability of solid propellant grains has been defined in terms of grain safety margins. However, many rocket motors with structural flaws (bore cracks, unbonds, etc.) have been fired successfully within ballistic tolerances. This indicates that conventional grain safety margins do not define adequately conditions which limit structural response of a solid propellant grain. Use of fracture mechanics techniques has been included in some motor service life predictions and eventually will become a routine characterization and evaluation requirement for all solid rocket motors. Some of the available fracture mechanics techniques are summarized, and laboratory fracture test methods, which should be considered for motor surveillance programs, are reviewed. Use of these fracture mechanics tools, together with crack combustion analysis recently developed at the University of Utah, provides a realistic assessment of structural defects and motor ballistic performance.

I. Introduction

HISTORICALLY, the structural reliability of solid propellant grains has been defined in terms of grain safety margins. However, many rocket motors with structural flaws (bore cracks, unbonds, etc.) have been fired successfully within ballistic tolerances. This indicates that grain safety margins do not adequately define the conditions which limit the structural response of a solid propellant grain. In the aerospace industry, many reports have demonstrated that cracked or flawed structures can function while sustaining considerable loads.[1-4]

The Air Force issued a new military standard in 1972 (MIL-STD-1530) to define structural requirements for military aircraft.[5] This standard introduced concepts of structural safety and durability which are related directly to service life.[6] The new requirements for damage-tolerant designs recognized that all structures have small flaws and defects at delivery. Structural durability is defined in terms of service life or time before unstable crack propagation. The contractor must demonstrate that the structure will last the required time by testing flawed structures.

The principles of this Air Force standard could be applied to specific solid propellant grains. Such an approach could be formalized by defining critical flaws in relationship to the motor ballistic response. The state-of-the-art of fracture mechanics for viscoelastic materials have progressed to the degree that fracture behavior can be considered in a reliability analysis. Two solid rocket motor loading conditions which are known to cause most structural failures are 1) thermal cooldown (and storage) and 2) rapid pressurization during ignition. Slow viscoelastic fracture can occur during storage over months or years and eventually lead to critically sized flaws, which would generate excess burning surfaces during pressurization. Subcritical thermal flaws or those which have propagated during storage may enlarge sufficiently during ignition to overpressurize a rocket motor. In some solid rocket motors, crack propagation may be slower than the propellant burning rate and be of no consequence. Critical flaws in solid rocket motors must be related to flaw growth rate as well as to flaw size.

Two major approaches to fracture have evolved for solid propellant applications: 1) the energy release method and 2) the stress intensity factor method. Variations of these techniques have been developed by Knauss,[7] Schapery,[8,9] Hufferd and Jacobs,[10] and Bennett and Anderson[11,12] for viscoelastic and nonlinear materials.

II. Fracture Analysis: Theory and Experiment

Energy Release Rate and Stress Intensity Factor Approach

The two major approaches to the study of fracture mechanics are 1) energy release and 2) local stress field. In the Griffith theory[13,14] the crack system is treated as a whole by assuming that cracks will propagate if the energy released by their growth, including work done by external loads, is greater than the energy required to create a new fracture surface. Others, notably Irwin,[15] have emphasized the stress conditions in the vicinity of the crack tip and that the critical intensity of the local stress field is a material constant, commonly referred to as K_c (fracture toughness). More recently, certain researchers in the solid propellant industry have favored the energy balance concept[16,17] while others have favored the stress intensity factor approach.[18,19] The equivalence of these approaches, for elastic stress analysis in a single mode, is well known. The relationship between the two concepts may be found, for example, in Ref. 20.

In using the energy balance approach, the strain energy release rate and the work done by external forces during a small increment of crack extension must be determined. Numerical techniques must be used for configurations with complicated geometry of loading. In two-dimensional problems, with only the opening mode present, the procedure is straightforward because the crack trajectory is known a priori to be along the initial crack direction. Two finite element analysis computer runs are made with slightly different crack lengths. Work done at the boundary W minus the change in strain energy U gives the energy available for crack propagation.

The stress intensity method is the alternate approach to fracture initiation and trajectory analysis. A number of methods are available for determining stress intensity factors. Since the stress intensity factor is proportional to the local stress field, and stresses may be superimposed. Handbooks of stress intensity factors may be used to construct the factors for a problem by superimposition, correction for edge effects,

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etc., so that a good engineering estimate may be obtained promptly. The energy release rates, on the other hand, are quadratic in stress, so that superimposition is not possible in multimode situations.

Numerous finite element methods, including crack opening displacement, local energy, energy release rate, and the J integral may be used to calculate K_I and K_{II}. Using crack opening displacement, K_I and K_{II} can be calculated from a single computer run. If a modern finite element program such as TEXGAP is used, the stress intensity factors K_I and K_{II} are calculated automatically, if the crack tip element is utilized.

Viscoelastic extension of the two primary fracture analysis techniques, which have been presented by Swanson,[21] Knauss,[7] Schapery,[8] and Francis,[30] have been applied to mode I fracture of viscoelastic materials. Another fracture growth criterion, developed by Jacobs and Hufferd,[22] is based upon local damage at the crack tip, as deduced from nonlinear studies of propellant behavior. All of the referenced viscoelastic fracture theories appear to give reasonable correlations with some limited range of experimental data. These theories are being evaluated with solid propellant on an AFRPL-sponsored Failure Mechanisms Program at Chemical Systems Division of United Technologies Corporation.

Experimental Methods

A variety of experimental methods has been developed to measure fraction initiation and velocity behavior with solid propellant materials. Most of these methods are constant rate, constant load, or constant strain loading modes of cracked biaxial sheets. Cracks may be located on the edge or central part of the specimen. Side cracked specimens have a nonsymmetrical load distribution and require a rigid alignment fixture using ball bushings or other sliding alignment equipment. Center cracked specimens generally have been used to obtain crack initiation from manufactured flaws. Single side cracked specimens have an advantage because the crack may propagate away from the inserted flaw to a natural crack tip region and still propagate far enough to obtain adequate crack velocity data before reaching the side of the specimen, where the edge effects alter the stress field. Fracture specimens generally have been obtained by a cut from redwood boxes or by postcure bonding with epoxy or other suitable adhesives.

Modulus relaxation with solid propellants occurs so rapidly that only limited velocity data can be obtained from the constant strain test modes. Most solid propellant characterizations have been conducted with constant rate or constant load test conditions. The potential differences in fracture data from inserted flaws (knife or razor blade) and the propellant's natural crack surface are being studied on the AFRPL Failure Mechanisms Program.

Typical data for the center cracked biaxial specimen and a constant rate loading mode are shown in Fig. 1 (from Layton and Bennett[23]) for a PBAN solid propellant. These data are presented for the energy release rate analysis method in which the fracture energy γ is obtained from a broad range of rates and temperature tests. Other data for the side cracked biaxial specimen and a constant load test mode are presented in Fig. 2. These data include the minimum K_I required to initiate fracture and the corresponding K_I vs crack velocity relationship. These data also were obtained over a range of test temperatures and shifted to form the master fracture toughness curve. When 75° F fracture testing was attempted at K_I greater than 120 psi in.$^{1/2}$ and velocities above 100 in./min, the entire test sample tended to disintegrate rather than fail at the crack tip region. This may be typical for high-rate propellant fracture. Both the energy release and stress intensity factor interpretation yield the equivalent fracture initiation information or minimum γ and K_{Ic} data.

Solid propellant fracture data exhibit the same pressure enhancement as found for propellant failure and modulus

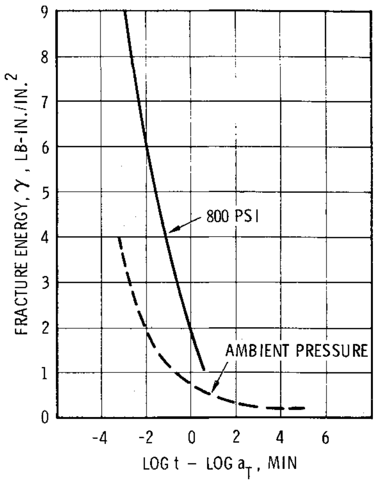

Fig. 1 Comparison of the ambient and elevated pressure energy function for motor propellant vs reduced time.

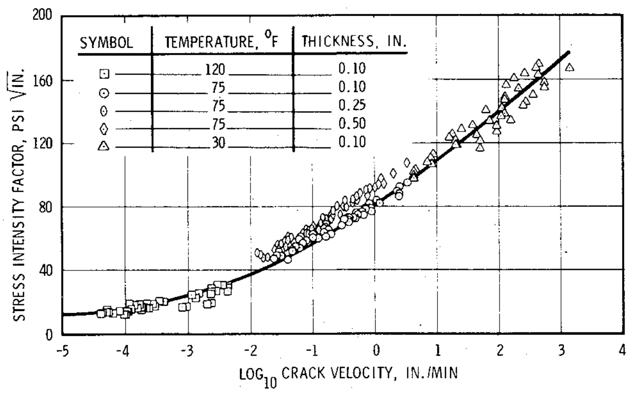

Fig. 2 Stress intensity factor vs crack velocity data for a PBAN propellant.

properties. A 35% improvement in fracture toughness was reported by Francis et al.[24] for a PBAN propellant tested in a 500 psi pressurized environment (Fig. 3).

Bond fracture initiation data have been evaluated with a broad variety of test techniques including bimaterial side cracked sheet, blister peel, and actual dissected specimens removed from rocket motors which include case, insulation, liner, and propellant. Data from these tests have not been related because of the large difference in material combinations and test details. Illustrations of some of these tests geometries are shown in Fig. 4. Viscoelastic fracture analysis of these multimaterial fracture test specimens is in a primitive condition; velocity data generally are not available. Cohesive fracture of solid propellant is much better understood and has been used for engineering analysis of solid propellant rocket motors; however, the best methods of evaluating and selecting efficient routine testing in a surveillance program remain to be determined.

The center cracked biaxial specimen appears to offer an advantage, because it can be used without alignment fixtures. Any laboratory that runs biaxial failure tests can conduct this fracture test without equipment modifications or additional training of test personnel. Primary data include crack initiation so the operator only needs to indicate the instant of initial crack propagation on the Instron load-time chart.

SRM Analysis and Crack Combustion Behavior

Elastic and viscoelastic analyses of SRMs have been conducted to determine if flawed structures would exhibit additional flaw growth during storage and ignition conditions. Analysis generally included the thermal and pressurization

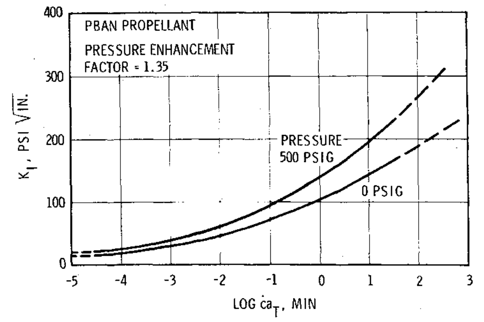

Fig. 3 PBAN solid propellant K_I crack velocity curves with and without superimposed pressure.

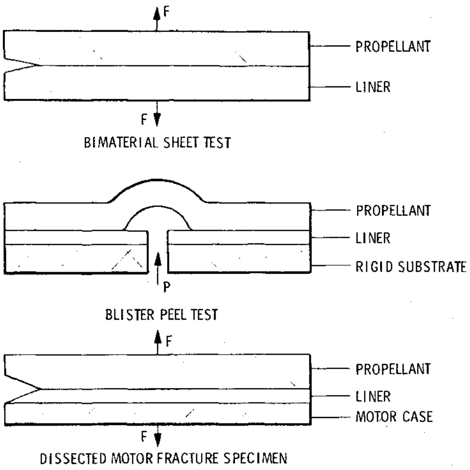

Fig. 4 Bond fracture test geometries.

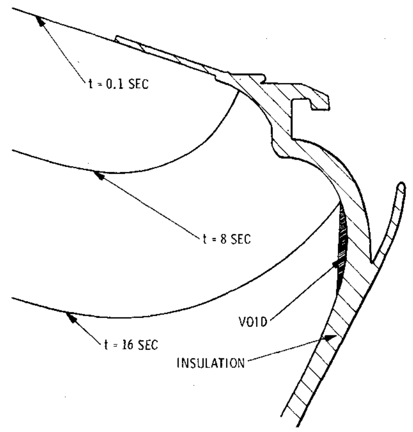

Fig. 5 Minuteman III, stage III aft end burnback configuration.

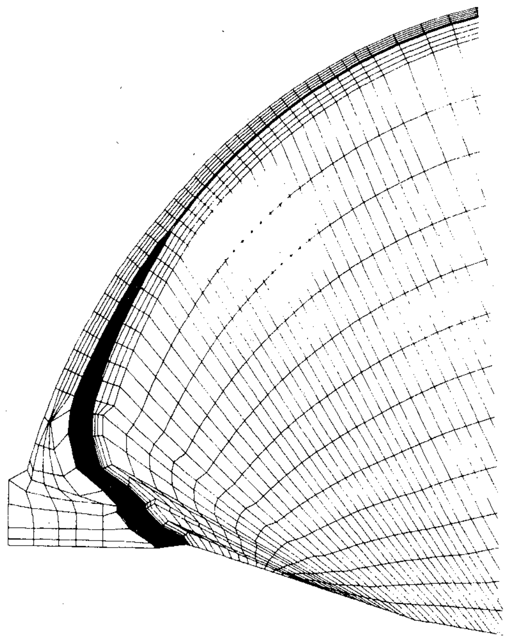

Fig. 6 11-in. debond subject to chamber pressures (0.1-sec configuration).

loads, but neglected the pressure buildup within the exposed flaws during ignition and burnback. A recent study was concluded at the University of Utah by Jacobs et al.[25] This effort assessed whether a flaw, crack, or debond would propagate mechanically because of combustion-induced pressure loadings. Available test data indicated that 1) burning would propagate into cracks and debonds and 2) propagation rate increased with increasing chamber pressure. Local pressures inside a burning crack can be much higher than the normal motor pressure and can contribute structural system and ballistic requirements for successful operation of solid rocket motors. To demonstrate the "crack criticality" results, a Minuteman III, stage III motor was analyzed for flaw propagation. This fiberglass case motor (Fig. 5) was cast with aft apex voids. The 0.1-sec. configuration was analyzed for unbonding around the aft end. Examples of both structural analysis grid deformations with and without burning in the unbond are shown in Figs. 6 and 7. Burning in the unbond significantly increases the propellant and case deformations, especially for the larger unbond regions. Analysis without crack burning would underpredict the fracture potential. A meaningful SRM reliability analysis should include fracture analysis with burning in the crack or unbond.

III. System Reliability Analysis

For system reliability analysis, the operational capability of a solid rocket is defined in terms of ballistic requirements such as thrust, pressure vs time, or specific impulse. As such, structural response is considered only when it relates to changes in pressure and/or thrust. Consequently, a reliability analysis has ballistic requirements as primary factors and structural anomalies as secondary factors. By this definition, operational motors can contain some bore cracks and unbond regions, if they do not alter ballistics significantly. When a structural failure does cause unacceptable deviation from required ballistic behavior, the flaw is considered critical.

By combining the fracture mechanics and ballistic reliability requirements, subcritical flaws, that can develop into critical flaws during operation, can be defined. These critical flaws should be included in the nondestructive test specifications because they can affect missile reliability. Since this method of analysis can relate flaw growth to structural loads, it can be used to accept a flawed missile for firing under restricted conditions, at a considerable cost saving. A description of this reliability analysis is shown in Fig. 8.

A similar approach also can be used for aged motors, if the fracture parameters are monitored in the motor surveillance program. The main difference is that nondestructive testing of aged motors is required to identify typical or specific flaw geometries, which are used as input to the fracture analysis. Aged fracture properties would be used in the analysis, and the reliability of the motor with typical flaws would be evaluated. Continued use of the motor can be based on a factual reliability evaluation, rather than engineering judgment or other subjective criteria.

One major problem, common to structural analysis and service life predictions, is the propellant modulus uncertainty. Safety margins and fracture probabilities are related directly

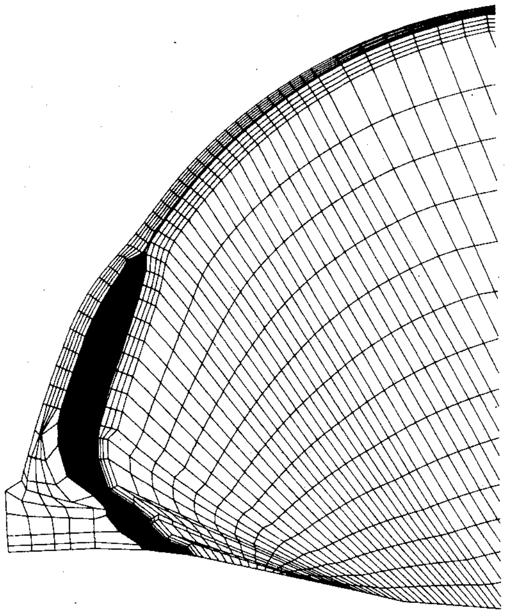

Fig. 7 11-in. debond subject to burning pressures (0.1-sec configuration).

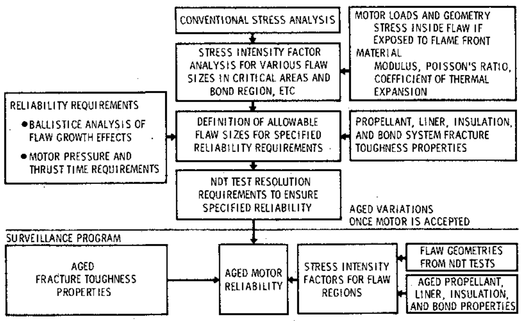

Fig. 8 Reliability analysis.

to the modulus used in this analysis. Apparent propellant nonlinearities and small strain test resolution difficulties have caused general confustion, sufficient to mask the real small-strain propellant modulus behavior. As a result, recently developed Aerojet nonlinear analysis computer codes were programmed to reject all small-strain data typical of motor applications, because the nonlinear curve fitting routines always generate large errors in the small-strain regions. Small-strain test data are suspect because the samples are damaged during machining, die cutting, handling, and pretest setup. Measuring the motor stresses directly and backing out effective modulus values, which could be used to correct the analysis calculations, is one way to avoid the modulus uncertainty question. However, motor stress transducers were found to be unreliable because of inadequate design, manufacturing, and application techniques. This problem is being reviewed in depth on an AFRPL-sponsored Improved Normal Stress Transducer Program, but some meaningful modulus number will still be required for comparison of stress analysis and measured stress data.

Other methods to measure reliably small strain modulus data for propellant should be reconsidered. Conventional small laboratory samples are not adequate because they are easily damaged by normal machining and handling. Large bulk-type specimens could be tested if they have a gage length large enough so that displacement values for small strains and stress values can be measured accurately. Rather than using routine ICRPG class B specimens, modulus data could be obtained with the large bulk samples over the stress, strain, and temperature range that SRMs experience. These bulk tests,

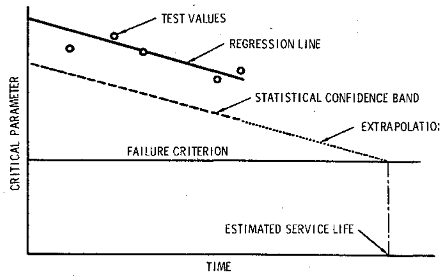

Fig. 9 Trend analysis.

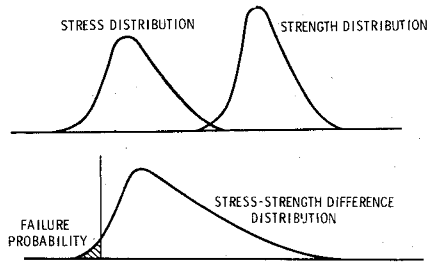

Fig. 10 Stress-strength joint distribution.

limited to small stress and strain values, would be conducted over long time periods.

Since all motor stress and fracture predictions are sensitive to modulus values, any change in modulus during age is reflected as a change in predicted motor stress level for fracture possibility. Many reported service life predictions are based on comparing aged failure properties with zero-time stress or fracture requirements. The entire motor structural analysis should be revised with changes in modulus, coefficient of thermal expansion, as well as changes in failure or fracture limits as reported in Ref. 26. Stress allowable/modulus ratios may define critical limits rather than just the stress values. This also applies to other critical parameters where a modulus increase with age may not change the grain safety margins, if the stress increases by the same factor. Generally, these two parameters have the same aging trends. This problem is illustrated in Fig. 9 (from Ref. 29), where the failure criterion is represented by a constant, and the aged test value is represented as a trend line and the intersection defining the estimated service life. In reality the failure criterion would have some age slope, similar to the critical age parameter. Thus, the two may never intersect, or the two lines could intersect at shorter times, if the slopes converged. This also can be shown in the probability of failure (Fig. 10) where stress and strength distribution have a small overlap which defines the failure probability. The aged mean value of both stress and strength distribution may change, such that the failure probability either increases, stays the same, or decreases at the motor ages. Even the distribution about the means may change with age and affect the failure probability without a change in mean values.

Assumptions used in past service life predictions may not be valid and should be reviewed. The computer calculated stress, strain, and fracture values may change with age to a greater extent than the failure and fracture limits, if the modulus changes are large (generally reported for age-sensitive propellants).[27,28] Holding either part of the service life analysis parameters as constants will reduce seriously the accuracy of the predicted motor life.

IV. Conclusions

1) Surveillance programs should include cracked biaxial sheet testing to determine changes in fracture parameters with age.

2) Surveillance programs should include some meaningful long time, small stress and strain modulus testing.

3) Service life predictions should include a complete fracture analysis which is updated periodically for propellant property changes measured in surveillance programs.

4) This fracture analysis should include burning in the crack, pressurized fracture data for ignition analysis, and long time unpressurized fracture data for thermal load analysis.

5) Service life prediction analytic assumptions should be reviewed in depth to insure that predictions are not biased by erroneous simplifying assumptions.

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