JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 36, No. 4, July–August 1999

Fracture Control of Space Flight Structures and Pressure Vessels

S. Sutharshana*
Angeles Crest Engineering, Inc., Pasadena, California 91103
J. B. Chang†
The Aerospace Corporation, El Segundo, California 90009
and
M. C. Lou‡
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109

The fracture control requirements and their implementation for the design and operation of NASA and U.S. Air Force space flight hardware are reviewed, with the focus on two categories of spaceflight hardware: 1) Space Shuttle payloads that include significant portions of the international space station under development and 2) flight pressure vessels. NASA and the U.S. Air Force have developed detailed fracture control requirements for Space Shuttle payloads and pressure vessels. Understanding these fracture control requirements and incorporating them early in the design phases of a program are important to cost effectively implement fracture control for space flight hardware.

Nomenclature

a = crack depth dimension
a_{cr} = critical crack size
a_f = final crack size
a_i = initial crack size
a_i^* = allowable crack size determined by crack growth analysis
c = half-crack-length dimension
K_c = fracture toughness of material
K_{Ic} = plane strain fracture toughness of material
N = number of cycles
t = part thickness
α = proof test factor
β_{cr} = geometric correction factor corresponding flaw size a_{cr}
β_i = geometric correction factor corresponding flaw size a_i^*
σ_{op} = operating stress level
σ_p = proof stress level
σ_{ys} = yield strength of material

Introduction

FRACTURE control is the application of design philosophy, analysis method, manufacturing technology, quality assurance, and operating procedures to prevent premature failure of hardware due to the propagation of undetected cracks or cracklike defects (or flaws) during fabrication, testing, transportation and handling, and service. Fracture control has been formally implemented in space programs beginning in 1970. NASA SP-8040[1] was the first document to specify the fracture control requirements for space flight hardware, and it was for pressure vessels in space flight systems. In 1972, the U.S. Air Force completed its development of a requirements document, MIL-STD 1522, for the design of pressurized space and missile systems. This document was revised in 1984 to become MIL-STD 1522A.[2] At present, MIL-STD 1522A is accepted as the primary requirements document for space flight pressure vessels.

Although fracture control methodology was being used in other industries, such as commercial and military aviation and the nuclear power industry, the Space Shuttle was the first space program to incorporate a comprehensive fracture control plan[3] for its design, development, and operation. There was no precedent for such usage on a space system inasmuch as it was a reusable, winged vehicle designed for 100 launches and landings.[4] After the Challenger mishap, NASA went through an extensive safety review of the Space Shuttle and its operations. One outcome of this review was that NASA developed a central fracture control document[5] for payloads and associated hardware to be flown on the Space Shuttle. At present, NASA STD-5003[6] (which is the revised version of Ref. 5) is the accepted requirements document for all payloads flown in the Space Shuttle, which include some key elements of the space station that are to be assembled in space around the turn of this century.

Received 27 June 1997; revision received 23 November 1998; accepted for publication 26 November 1998.

*Director. Senior Member AIAA.

†Senior Engineering Specialist, Structures Department. Member AIAA.

‡Deputy Section Manager, Science and Technology Development Section. Associate Fellow AIAA.

Payload Requirements

For a flight payload system to be flown in the Space Shuttle, the design and use of each of its hardware components must be reviewed to determine whether a preexisting crack in the component may lead to a catastrophic hazard. A catastrophic hazard is defined as an event that can disable or cause fatal personnel injury or loss of the Space Shuttle. Examples of such events include a failure and a subsequent release from a payload of any part or fragment having mass and or energy that can potentially punch through the wall of the cargo bay, a release of a significant amount of hazardous substance into the cargo bay, or a failure that prevents closure of the cargo-bay door. The NASA payload requirements document[6] contains the procedures for fracture control classification of all payload components, as shown in the flowchart in Fig. 1.

Nonfracture Critical Categories

Components classified as exempt parts, low-released-mass parts, contained parts, and fail-safe parts are not fracture critical. They can be processed under conventional aerospace industry verification and quality assurance requirements. Exempt components are those that are clearly nonstructural and not susceptible to failure as a result of crack propagation. Components that may be included in exempt category are insulation blankets, wire bundles, and elastomeric seals.

The total released mass, the fracture toughness of the part material, and if the part is preloaded in tension will determine whether a component may be categorized as a low-released-mass part. A preloaded, low fracture toughness component with a mass less than 13.6 g (0.03 lb) whose failure will not result in the release of a larger part may be classified as a nonfracture critical part. A part is considered to have low fracture toughness when its material property ratio $K_{Ic}/\sigma_{ys} < 1.66\ \sqrt{\text{mm}}$ (0.33 $\sqrt{\text{in.}}$). However, this mass may be as high as 113.5 g (0.25 lb) if the part is not preloaded and is made of high fracture toughness material. Alternatively and for

Table 1 Minimum initial crack sizes based on NDE method

Crack location	Part thickness t, in.	Crack type	Crack dimension a, in.	Crack dimension c, in.
		Eddy current NDE		
Open surface	≤0.050	Through	t	0.050
	>0.050	PTC[a]	0.020	0.100
			0.050	0.050
Edge or hole	≤0.075	Through	t	0.100
	>0.075	Corner	0.075	0.075
		Penetrant NDE		
Open surface	≤0.050	Through	t	0.100
	$0.050 < t \leq 0.075$	Through	t	$0.15 - t$
	>0.100	PTC[a]	0.025	0.125
			0.075	0.075
Edge or hole	≤0.100	Through	t	0.100
	>0.100	Corner	0.100	0.100
		Magnetic particle NDE		
Open surface	≤0.075	Through	t	0.125
	>0.075	PTC[a]	0.038	0.188
			0.075	0.125
Edge or hole	≤0.075	Through	t	0.250
	>0.075	Corner	0.075	0.250
		Radiographic NDE		
Open surface	$0.025 \leq t \leq 0.107$	PTC[a]	$0.7t$	0.075
	>0.107		$0.7t$	$0.7t$
		Ultrasonic NDE		
Open surface	≥0.100	PTC[a]	0.030	0.150
			0.085	0.085

[a]Partly through crack.

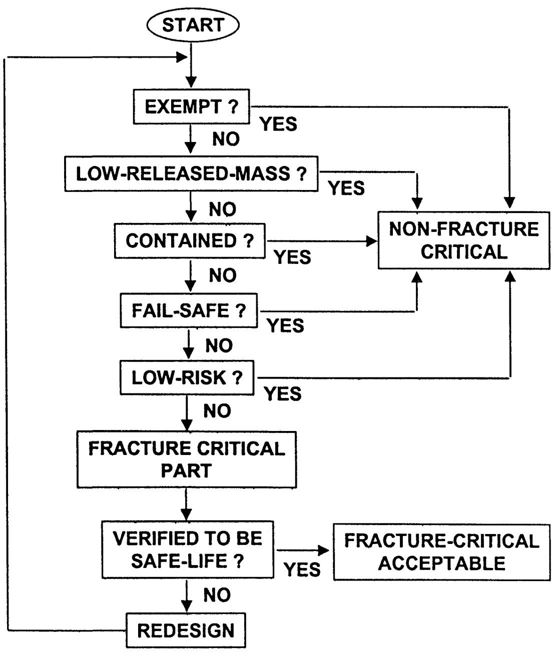

Fig. 1 Fracture control classification process.

Space Shuttle payload parts, the total mass in grams supported by a low-released-mass part cannot be more than $1.94/h$, where h is the parts direct travel distance in meters ($14/h$ when h is in feet) to the aft bulkhead of the Space Shuttle cargo bay.

A payload component may be classified as a contained part if its failure and subsequently the failure of its container do not result in the release of elements with a combined mass exceeding the low-released-mass limit. Documented judgment may be used when it is clear that sufficient containment exists, such as in case of a metallic box containing closely packed electronics, detectors, or cameras. In general, the containment capability may be assessed by test or analysis. An empirical analytical approach that is often used calculates the required thickness of the container by equating the kinetic energy of the released fragment to an estimate of the work required to punch out a hole from the container wall. In addition to the perforation analysis, it must be assessed as to whether the container will continue to perform its function without creating additional hazards.

The fail-safe category, in general, applies only to redundant structural designs that are not classified as pressure vessels or high-energy rotating equipment. In addition to being deemed redundant, a fail-safe design should ensure that fragments from a failed structural element do not exceed the low-released-mass limit. An example of a fail-safe component may be an electronic box attached with multiple fasteners. After failure of one fastener, it must be shown that the remaining fasteners can still withstand the redistributed loads with a minimum ultimate factor of safety of 1.0.

Fracture Critical Components

All of the parts that cannot be classified as nonfracture critical are deemed fracture-critical parts. Fracture-critical components should have their damage tolerance and/or safe life verified by either test or analysis. The safe-life analysis should be performed based on the state-of-the-art fracture mechanics principles. A part satisfies safe-life criteria when nondestructive evaluation (NDE) is performed to screen out cracks above a particular size and then show by analysis or test that an assumed crack of that size will not grow to failure when subjected to the cyclic and sustained loads encountered during four complete service lifetimes. The selection of NDE methods and level of inspection should be based on fracture mechanics analysis and the safe-life acceptance requirements of a specific part. The minimum initial crack sizes for safe-life analysis using different NDE methods are shown in Table 1.

A proof test logic is sometimes used to establish a crack size for safe-life analysis. If a structure passes the proof test, then the knowledge of the fracture toughness and the proof load level allows the determination of the maximum crack size that may have existed after a proof test. This crack size is given as follows:

$$a_i = \frac{K_c^2}{\beta^2 \pi \sigma_p^2} \quad (1)$$

This maximum crack size from the proof test can be used as the initial flaw size for the safe-life analyses. To determine the initial flaw size by means of the proof test logic, an upper bound value of the fracture toughness should be used because this will result in a larger more conservative initial flaw size. Figure 2 shows the procedure for the simple case of constant amplitude loading.

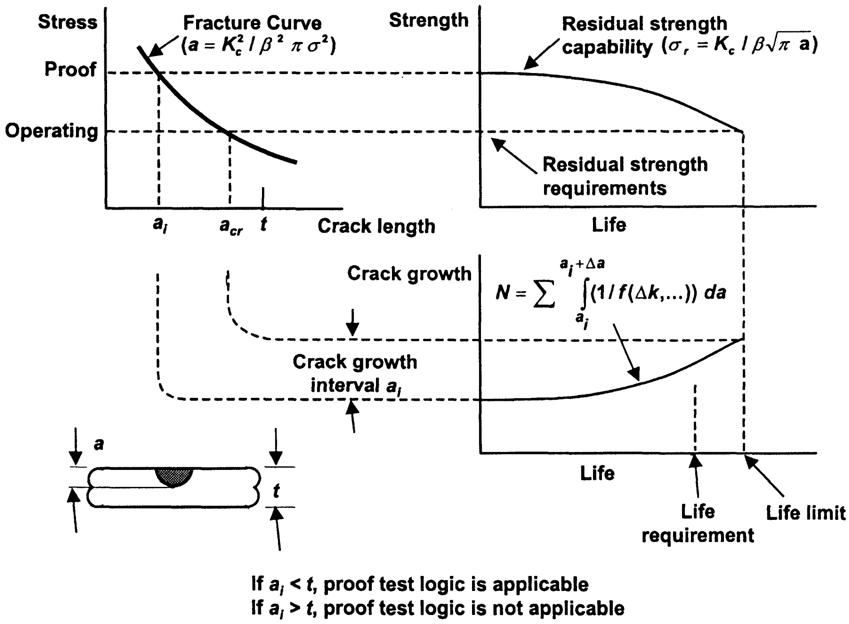

Fig. 2 Proof test logic to determine initial flaw size for safe-life analysis.

Although it is conceptually possible to use the proof test logic on any structure, practical constraints limit the type of structure for which proof testing may be a viable crack screening technique. An important criterion is that proof test loads must exceed the magnitude and match the direction of all significant flight loads of the part. It is economically feasible to achieve this only when the loads in a part are simple, well defined, and arise from a single type of external loading. Fasteners, pressure vessels, and strutlike members are good candidates for proof testing.

One complete service lifetime that is used in a safe-life analysis includes all significant loading events that occur after NDE or a proof test. Software codes with proven methodology and reliable material database, such as NASA/FLAGRO (NASGRO),[7] should be used to perform the required safe-life analyses. Crack growth analysis of composite materials is beyond the current state of the art. The fracture control requirement for composite structures is satisfied by proof testing it to 1.2 times the limit load and through NDE. Reference 5 also allows for an approach to keep the limit load strains below a threshold strain level at which the composite is damage tolerant.

Pressure Vessel Requirements

All space flight pressure vessels are designated as fracture critical. Reference 2 offers two approaches, namely, A and B, as shown in Fig. 3, for design analysis and verification of pressure vessels. Approach B, which complies with the American Society of Mechanical Engineers pressure vessel code, is seldom used for flight vessel development because it results in an overweight vessel.

Thus, approach A is the only one applicable for flight vessels. Two paths may be followed in this approach, based on whether the failure mode is 1) leak before burst (LBB) with nonhazardous contents, or 2) brittle (non-LBB) or LBB with hazardous contents. The LBB failure mode may be demonstrated by analysis or test by showing that an initial flaw shape (given by ratio of crack depth a to half-length c) in the range $0.05 \leq a/c < 0.5$ will propagate through the thickness of the pressure vessel before becoming critical at the maximum expected operating pressure (MEOP). Alternatively, a ductile fracture criteria contained in MIL-STD 1522 provides an acceptable approach for failure mode determination. A pressure vessel is considered to exhibit a ductile fracture mode (LBB) when

$$K_{Ic}/\sigma_{op} \geq 2a\sqrt{t} \qquad (\alpha\sigma_{op} \leq \sigma_{ys},\ \alpha > 1) \tag{2}$$

For the LBB path in approach A, no further fracture mechanics analysis is required when Miner's rule is satisfied by a fatigue analysis of the unflawed vessel. Qualification testing of the vessel requires an LBB demonstration (waived if shown analytically), pressure testing, and random vibration testing. Pressure testing requires that there be no yield after pressure cycling for either 1) 2 × number of operating cycles at 1.5 × MEOP or 2) 4 × number of operating cycles at 1.0 × MEOP, and there be no burst when pressurized to burst factor (BF) × MEOP. Acceptance tests conducted on each pressure vessel before commitment to flight require an NDE and a proof pressure test. The proof test is intended to detect any errors in the manufacturing process or workmanship and in the specification of the materials. Most flight pressure vessels are designed to a BF of 1.5.

For the brittle or LBB with hazardous contents path in approach A, safe-life analysis (or test) of the vessel is required with a pre-existing initial flaws to show that life is greater than four times the service life of the vessel. Safe life of the vessel is the period during which it is predicted not to fail in the expected operating environment. The requirements for qualifying the vessels by pressure testing and random vibration are the same as for path 1. However, the acceptance tests in this case would be required to establish the initial flaw size used in the safe-life analysis in addition to detecting any errors in the manufacturing.

The proof test factor based on the safe-life analysis is determined by

$$\alpha = \sqrt{(a_{cr}/a_i^*)[\beta_{cr}/\beta_i]} \tag{3}$$

Figure 4 shows schematically how the initial allowable flaw size is determined by backtracking 4 × service lifetimes along the a vs N curve from the critical flaw size. In other words, a flaw of size a_i^* will survive four times the service life after a successful proof test.

The current trend for space flight vessels is to use materials with relatively high fracture toughness, such as annealed titanium and cryo-stretched 301 stainless steel. The typical vessel thickness is less than 0.050 in. Hence, the proof-test logic-based initial flaw size given by Eq. (1) may be greater than the wall thickness of the tank.

Recently, Ref. 2 has been updated by the The Aerospace Corporation. A draft copy of the updated standard, which specifies the safe-life demonstration requirement for pressurized structures containing hazardous fluids, such as launch vehicle main propellant tanks, has been reviewed by government agencies and aerospace industries. This updated military standard is being converted into an industry standard, which consists of two volumes. The first volume covers metallic pressure vessels (spacecraft liquid propellant storage tanks and high-pressure gas bottles), pressurized structures (launch vehicle main propellant tanks), special pressurized equipment (batteries, heat pipes, cryostats and sealed container) and pressure components (lines, fittings, valves, and hose).

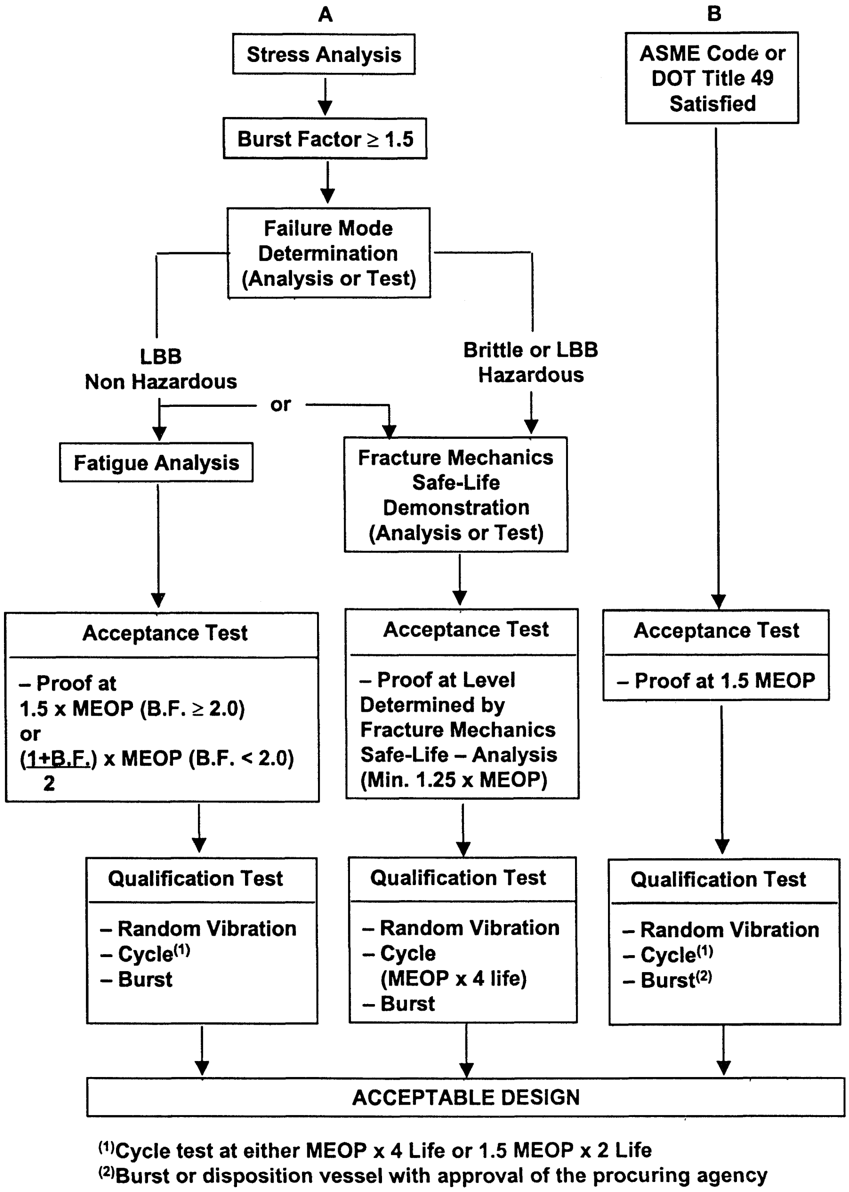

Fig. 3 Approaches for design and verification of pressurized components in Ref. 2.

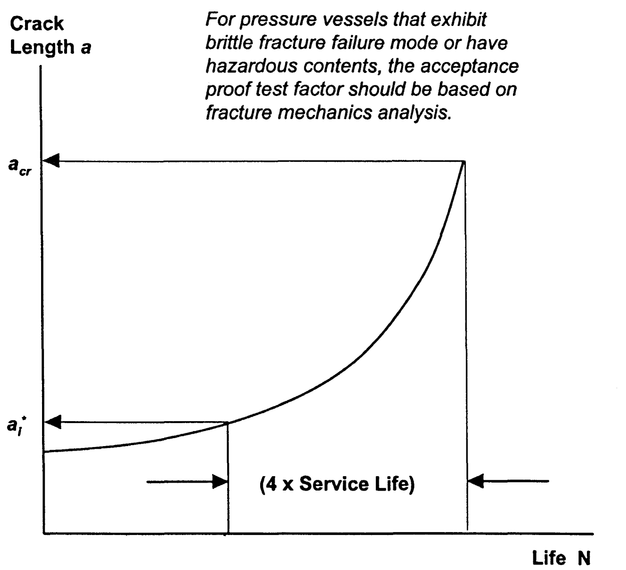

Fig. 4 Estimating initial allowable flaw size a_i^* to calculate proof factor α.

Implementation Issues

The most important aspect of cost effectively implementing fracture control for flight hardware is to prepare a safety verification plan that incorporates the relevant fracture control requirements early in the program. It is important to make the designers and analysts also aware of the requirements and damage-tolerant design approaches at the onset because most structural parts can be designed tolerant of initial flaw without significantly complicating the design or adding much cost. Every effort should be made to design the components of space hardware so that they fall into one of the nonfracture critical categories described in the "Payload Requirements" section. However, the fracture critical category cannot be avoided for components such as pressure vessels and those having high-energy rotating parts, and parts that need to be made with brittle materials, welded joints, composite materials, or bonded joints.

Despite having four available nonfracture critical categories, implementing the requirements for certain Space Shuttle payloads resulted in extensive fracture critical parts lists. However, most of these parts either carried very small loads, or were made of highly ductile material and were made with processes in which initial cracks are extremely unlikely. An outcome of this was the creation of yet another nonfracture-critical category, called low-risk parts in the revised NASA-STD 5003 document.[6] Low-risk parts must be made from metal highly resistant to fracture with well-established processes and demonstrate low probabilities of crack presence and growth.

Some modifications and exceptions to MIL-STD 1522A,[2] are specified in NASA fracture control requirements document for Space Shuttle payloads.[6] To accommodate the use of one-of-a-kind vessels, NASA allows a proof test at a minimum of $1.5 \times$ maximum design pressure and a fatigue analysis showing a minimum of 10 design lifetimes in lieu of the burst and fatigue life tests required by Ref. 2. NASA requires an additional NDE of the welds in the pressure vessel shell after proof testing to screen the initial NDE flaw size assumed for analysis.

As mentioned in the Introduction the Space Shuttle was the first space program to incorporate a comprehensive approach to prevent structural failures resulting from cracks or cracklike defects. Fracture control plans were developed for the Orbiter, solid rocket booster, main engine, and external tank. It was planned to produce five flight vehicles, and Orbiter test verification for safe life would have been relatively costly (in terms of total program costs) compared to similar verification tests for commercial and military aircraft programs. Hence, fracture control requirements were met for the Space Shuttle program by a mixture of analysis and test.

The safe-life analyses for the Space Shuttle components were performed primarily using FLAGRO, which was a predecessor to the present NASGRO. In the Apollo program, fracture mechanics analyses were mainly used for the safe-life verification of pressure vessels, and the proof-test logic was used to determine their initial defect sizes. On the Space Shuttle, the proof-test logic could not be used because most of the vessels were thin-gauge type, and the pressure vessels were not fracture critical at proof stress levels. Hence, NASA and the Space Shuttle contractors developed quantitative NDE procedures by performing numerous tests on detection of flaws on flat aluminum panels and welded titanium panels. The flaw detection results showed that some inspectors consistently detected smaller defects than others, and specific methods and equipment improved the sensitivity of the NDE. Thus, two categories, namely, standard NDE and special NDE, were established. To use new higher strength materials for spaceflight pressure vessels, NDE techniques that can reliably detect smaller initial defects in thin wall pressure vessels have to be developed.

Conclusions

Fracture control requirements for payloads in the Space Shuttle classify each of its components to be categorized as either fracture critical or not fracture critical. To minimize impact in schedule and cost, every effort should be made early to design the components in the payload to fall into one of the nonfracture-critical categories provided in the payload requirements. All space flight pressure vessels are classified as fracture critical. Designing lighter weight pressure vessels using new higher strength materials will need the development of improved NDE techniques that can detect smaller initial defects to meet the fracture control requirements cost effectively.

Acknowledgments

The work reported here was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA, and by The Aerospace Corporation, under a contract with the U.S. Air Force.

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R. B. Malla
Associate Editor