Proposed Reliability-Based Damage Tolerance Guidelines for Space Systems

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Deterministic damage tolerance guidelines for highly reusable and efficiently designed launch systems can be challenging to meet and result in overly conservative assessments for tightly controlled manufacturing processes. Deterministic approaches may be unconservative when the structure is workmanship sensitive and there is high variability in fracture properties. Reliability-based damage tolerance assessments targeting a component reliability over the service life commensurate to mission risk posture is a promising alternative. Low production rates, short fleets, and lack of standards or guidance has slowed down widespread adoption of this method. Guidance for the robust application of reliability-based damage tolerance for space systems are proposed. These guidelines cover the treatment of uncertainty in damage tolerance analysis, the collection of data to develop probabilistic distributions, uncertainty propagation methods, and types of hardware.

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I. Introduction

To support rapid launch response and shorten processing time between launches, there is a concerted effort by the launch industry to develop, build, an increase the resiliency of the fleets of launch vehicles. Current damage tolerance practices for analyses could be in some instances to be conservative such as a safe design may not be able to meet requirements. Achieving large service lives requires re-examining the approach for assessing damage tolerance.

A common damage tolerance approach used in the aerospace industry is to perform a deterministic assessment assuming an initial flaw exists in the hardware. The size of the initial flaw is chosen to be greater than or equal to the minimum flaw size which can be detected using non-destructive inspection (NDI) with 90% probability of detection at a 95% confidence level (P90/C95). If the characteristics of the flaw are unknown, the analysis must consider the worst-case location(s) and orientation(s) while accounting for interaction effects from adjacent or nearby flaws. If the

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flaw characteristics are known, the analysis uses those characteristics. Average or typical values of fracture toughness and fatigue crack growth rate are used in the assessment. The component with this initial flaw must survive at least four times the predicted service life.

Depending upon the organization, the factor of four in the life assessment has accounted for all or dome of the following: uncertainty in fatigue and fracture properties, build-to-build variation in component geometry, and analytical uncertainties in stress predictions, stress intensity factor calculations, and interpolation error in crack growth rates [1]. There is lack of consensus on what the factor of 4.0 accounts for, and that drives the need for exploring more quantitative approaches such as probabilistic methods.

[1].

This approach is referred to as the deterministic damage tolerance analysis (DDTA). This approach is generally agnostic to manufacturing methods and does establish component reliability. The approach is generally conservative when applied to components manufactured using methods that rarely produce flaws, such as traditional subtractive machining from wrought plate, but less conservative for components made with processes that regularly generate flaws or have highly variable fatigue or fracture characteristics, such as manufacturing methods that are prone to producing flaws just below the inspectable size.

Alternatively, a reliability-based damage tolerance analysis (RDTA) approach could enable quantifying the component reliability based on measured inputs that are closely tied to the manufacturing method. This probabilistic fracture mechanics approach (PFM) necessitates probabilistic distributions describing each relevant input parameter to a crack growth analysis. The uncertainty in the input variables is propagated through a crack growth analysis to determine the component reliability for the planned mission life. One key difference between the DDTA and the RDTA is that the initial flaw size in DDTA is based on the NDI capability while the initial flaw size distribution in RDTA is based on the actual population of defects existing in flight components. Using an actual representative population of defects can allow RDTA to demonstrate reliability for components which may not show sufficient damage tolerance life using an initial flaw size based on the NDI capability alone. A hybrid approach could also be used, where the RDTA is based on a deterministic flaw size, while other inputs such as geometric dimensions, properties, and loads are treated as random variables.

A probabilistic method for damage tolerance assessments has been adopted in certain industries such as aviation and nuclear sectors. In the aviation sector, these reliability-based approaches have been adopted to guide the timing of the interval of inspections to inform timely identification of an imminent component failure. Inspections reduce the likelihood of fatigue failure in actual flight and a risk analysis can be conducted to assess the overall structural integrity of the aircraft. The Federal Aviation Administration (FAA) Advisory Circular published guidance on the use of PFM for damage tolerance verification of aircraft engine components. This guidance included reliability targets, default NDI probability of detection (POD) curves for typical inspection methods, and initial flaw size distributions for engines made of titanium [2, 3]. Significant underlying work was required to develop the database containing production data and inspection data, which then allowed for the robust use of these methods. In the nuclear power industry, the Nuclear Regulatory Commission (NRC) published guidance on the use of PFM for reactor and nonreactor license submittals, focusing on the technical details of reliability analyses [4, 5].

In the space industry, low production rates, short fleets, lack of data on specific manufacturing methods (e.g., bellows, additive manufacturing) and lack of standards or guidance has prevented adoption of this method. Proposed guidelines are proposed herein to facilitate adoption of RDTA in the space industry. This work is a starting point for discussions at future workshops intended to develop industry consensus on how reliability-based approaches can be incorporated into damage tolerance assessments. The aim is to better quantify component reliability, increase reusable service life when possible, and tightly couple the manufacturing method with component reliability.

II. Crack Growth Analysis Guidelines

Reliability-based damage tolerance analysis (RDTA) calculates life at a specified level of reliability by modeling the key input parameters as random variables rather than deterministic values. Using a reliability framework, the assumptions applied to DDTA may be relaxed if appropriate data are collected. Not all inputs need to be modeled with random variables in an RDTA. If any inputs are modeled as random variables, then a probabilistic crack growth analysis should be performed.

Allocated component reliability based on mission risk posture should be defined to enable RDTA assessments. The RTDA should meet allocated component reliability defined by the program.

A. Initial Flaw Size

The initial flaw size used in the analysis should be one of the following:

- The smallest flaw detectable by NDI with 90% probability and 95% confidence (P90/C95).
- An upper bound developed through inspection of representative components.
- Treated as a random variable characterized through inspection of representative components.

Guidelines for determining the initial flaw size to use in the analyses are in Section **Error! Reference source not found.**.

B. Inspection Simulation

When the initial flaw size is modeled as a random variable, it is no longer tied to the NDI capability. Proceeding with the RDTA without simulating the inspection process assumes that no inspections are performed, which results in conservative reliability predictions.

Inspection simulation may be included in the RDTA to model the process of inspecting and dispositioning hardware. Inspection simulation uses a probability of detection (POD) curve which relates the probability of detecting a flaw to its size.

If a P90/C95 POD curve has been developed through POD studies per NASA-STD-5009 [6], then that curve may be used for inspection simulation in the probabilistic crack growth analysis.

If a standard NDI consistent with NASA-STD-5009 is used to inspect the component, the standard flaw sizes for the NDI method may be used as a basis for developing the POD curve. The POD can be assumed to be 0% for flaws smaller than the standard flaw size and 90% for flaws larger than that size. Special or non-traditional NDI may require different treatment.

C. Crack Location and Orientation

The flaw location should be modeled using one of the following options:

1) Modeled as a random variable: When modeled as a random variable, the spatial distribution of flaws throughout the component should be supported by a physical understanding of the manufacturing process.

2) Location/orientation corresponding to minimum life: The flaw should be assumed to be in the orientation resulting in minimum predicted life unless data exists to characterize the effect of flaw orientation on the crack growth rate.

3) Determining the worst-case location and orientation often requires performing the crack growth analysis at several candidate locations and orientations and choosing the location resulting in minimum life.

D. Loads and Durations

Load spectra (i.e., number of cycles, duration, and amplitudes) should be modeled using at least one of the following options:

- Assumed to be at the P99/C90 limit level and/or maximum expected operating pressure characterized through a fluid system analysis and/or dynamic loads analyses
- Modeled as probabilistic random variables characterized through simulations, ground testing, and flight data.

Some load events may be modeled as probabilistic random variables while others may be modeled using a deterministic approach, as above. When using P99/C90 to define limit load, resulting reliability estimates may be conservative.

E. Material Properties, Geometric Variation, and Life Factor

In the RDTA, the required life factor depends on which variables are modeled as random variables and which are treated deterministically. Possible combinations of modeling methods for material properties and geometric variation are shown in Table 1.

The RDTA should use a combination of modeling methods for crack growth rate, fracture toughness, and geometric variation listed in Table 1. The analysis should use the corresponding life factor specified in the table row.

Table 1: Modeling methods for material properties and geometric variation - Allowed combinations and required life factors

Crack Growth Rate and Fracture Toughness	Geometric Variables	Required Life Factor
Average Properties	Nominal Geometry	4.0 per AIAA-S-110 [7]
Average Properties	Random Variables	4.0
Random Variables	Worst-Case Geometry	None
Random Variables	Random Variables	None

When material properties are treated as random variables, but geometry is treated deterministically, the worst-case geometry should be assumed in the analysis (e.g., minimum component thickness, minimum corner radius, etc.). Effects of the worst-case geometry on steady-state and cyclic stresses should be evaluated. When treating geometry as a random variable the correlation between the component geometry and local stresses should be included in the RDTA. For example, the effect of wall thickness or fillet radius variation should be reflected in the stresses used in the crack growth analysis.

Correlations between crack growth rate, fracture toughness, crack growth threshold, and strength properties should be accounted for in the RDTA. Not accounting for correlations can result in unconservative reliability calculations. For example, lot of material with low fracture toughness may also have low strength and faster crack growth rate. If these are truly independent, it is unlikely for them to be degraded simultaneously. However, if they share a common cause (i.e., a below-average batch of material), having low properties for all 3 may be more common than expected.

III. Data Collection Guidelines

When any inputs to the RDTA are modeled as random variables, it is important that the input distributions are accurately characterized. Guidelines are proposed related to data collection and distribution characterization to ensure that the random variables used in the RDTA are sufficiently accurate to achieve trustworthy reliability predictions.

A. Determining the Initial Flaw Size

In an RDTA, uncertainty in the initial flaw size is often the most important parameter influencing the probability of failure. The initial flaw size may be treated deterministically or probabilistically.

1. Deterministic NDI Initial Flaw Size

If NDI consistent with NASA-STD-5009 is used for component inspection, the standard initial flaw sizes documented in NASA-STD-5009 may be used as the initial flaw size in the damage tolerance analysis. Alternatively, if POD studies consistent with NASA-STD-5009 have demonstrated the NDI method detects a smaller flaw size at the P90/C95 level, the qualified flaw size may be used as the deterministic initial flaw size in the damage tolerance analysis.

2. Deterministic Upper Bound Flaw Size

When sufficient data is available, the initial flaw size used in analysis may be an upper bound estimated through hardware inspections. Depending upon the risk posture and reliability requirements for the hardware an upper bound flaw size may be developed at a probability and confidence level. A starting point could be utilizing an A-Basis type approach, where the upper bound flaw size bounds 99% of hardware builds with 95% confidence.

One of the following approaches should be used to develop this upper bound size:

For hardware made using well-controlled manufacturing methods, the following reduced sample size method may be used. A well-controlled manufacturing method is one with locked down (e.g., key process parameters identified and controlled) and optimized process parameters which has been shown to produce consistent material properties and component quality.

1. Perform fatigue testing using one of the following options:
    a. Fatigue test 1 component to 4 times the service life
    b. Fatigue test 2 components to 2 times the service life
    c. Fatigue test 5 components to 1 service life
2. Post-test destructively inspect each component and subject the component to a volumetric high-resolution inspection method such as micro-CT
3. If any crack-like indications are identified by high-resolution inspection:
    a. Record the size of each detected crack
    b. Fit an extreme value distribution to the crack sizes using a Peaks over Threshold (POT) or block maximum approach
    c. Use this distribution in RDTA, or calculate an upper bound initial flaw size from the distribution
4. If no crack-like indications are identified by high-resolution inspection:
    a. Evaluate the detectable crack size of the high-resolution inspection
    b. Use the larger of the minimum detectable crack size or 0.005" as the initial flaw size or larger if informed by hardware handling observations (e.g., nicks, scratches).

This method is only recommended for hardware suspected to rarely contain cracks. If this sparse testing shows cracks larger than 0.005, then this process is not valid for finding an upper bound. When applied to hardware made using materials or processes which occasionally produce cracks, there is a risk that the small number of fatigue tested components may not be representative of the population. If this occurs, the initial flaw size will be underestimated. NDI of hardware manufactured using that method may be used to "prove" a manufacturing method is unlikely to produce flaws. A proposed number of inspections for hardware manufactured using various manufacturing methods is shown in Table 2. The number of inspections may be tailored based on component reliability requirements.

Table 2. Manufacturing process categorization and suggested number of inspected components to demonstrate low likelihood of flaw production

Process Category	Process Examples	Number of Inspections Suggested
Machined Wrought	• Machining plate, bar, and other metal stock with raw stock UT inspection • Machining forgings with raw stock UT inspection	None
Cold / Hot Forming	• Metal spinning, flow forming, and forging processes without full surface machining post-forming • Rolling, extruding, sheet metal bending	14
Solid State Metallic Joining	• Friction stir welding • Friction & inertia welding	14
Melting & Fusion Processes	• Castings • Fusion welds, brazing, solder joints • Additive manufacturing processes	70

The number of required inspections varies by process category based on prior knowledge about the likelihood of manufacturing processes producing flaws. For example, more evidence is required to prove that a fusion welding process produces no flaws than is required to prove that machining wrought plate stock produces no flaws.

For any hardware, the following approach may be used to determine the deterministic upper bound flaw size:

1. Perform standard NDI consistent with NASA-STD-5009 on a number of components commensurate with the desired statistical enclosure level
2. If any crack-like indications are detected:
    a. Record the size of the largest detected crack-like indication on each component
    b. Fit an appropriate extreme value distribution to the maximum flaw sizes
    c. Calculate a statistical upper bound flaw size from the extreme value distribution (e.g., 99th percentile of the distribution, accounting for sample size uncertainty at 95% confidence level)
3. If no crack-like indications are detected:
    a. Fatigue test one component to four times the service life
    b. Destructively inspect the component, looking for signs of crack initiation
    c. If no crack initiation is found, use a 0.005” flaw as the initial flaw size or higher depending upon handling hardware observations (e.g., scratches, nicks, etc.)
    d. If crack initiation is present, measure the post-test flaw sizes and back-calculate the initial flaw size using crack growth software such as NASGRO
    e. Use the larger of the back-calculated initial flaw size or 0.005” as the initial flaw size

In the second method, the sample size is chosen such that the largest flaw observed among the inspected components bounds the desired fraction of the population. Note that this method operates under the assumption that a large number of units were inspected. The relationship between the desired enclosure level and required number of components calculated using a binomial distribution is tabulated in Table 3. If no cracks are found among the components, one can be reasonably sure no structurally relevant flaws are present even if the inspection method does not reliably detect the smallest flaws. Inspection of different components can count towards the sample size requirement if similarity rationale exists considering geometry, materials, manufacturing method, and inspection technique. Generally, components made from the same material with similar geometry made on similar tooling and the same manufacturing processes may be pooled together.

Table 3: Suggested number of inspections to achieve desired statistical enclosure level

Proportion of Population Bounded by Largest Detected Flaw	Required Number of Inspected Components for 50% Confidence	Required Number of Inspected Components for 90% Confidence
0.999	693	2302
0.995	139	460
0.990	69	230
0.950	14	45
0.900	7	22

An extreme value distribution is recommended in the second method because the distribution models the maximum of many samples of other random variables, which reasonably models the distribution of the largest flaw present on each part. When a distribution is fit to the detected flaws, it is expected to be more conservative than the underlying flaw size distribution. Most inspection methods are more likely to detect larger flaws, skewing the distribution of detected flaws larger.

3. Probabilistic Initial Flaw Size Distribution

The probabilistic flaw size distribution may be characterized using a variety of methods. At least one of the following methods should be used:

- High-resolution NDI, such as micro-CT scanning several flight-quality components
- Destructive inspection and sectioning of several flight-quality components
- Back-calculation of initial flaw sizes from flaws detected in retired hardware or after fatigue testing [8, 9]
- Review of historical NDI records of the part

When a review of historical NDI records is used as the only method to build a flaw size distribution, the data should be processed to account for the capability of the inspection method, i.e., the likelihood that flaws may have been missed.

The initial flaw size distribution should be determined from flaws detected across several components. The number of components should be commensurate with the required reliability and confidence level. The intent of this guideline is to account for build-to-build variability, and to avoid fitting the distribution to flaws detected on a single non-representative part.

B. Inspection POD Curves

If inspection simulation is included in the RDTA, minimum detectable flaw sizes and/or POD curves should be developed per NASA-STD-5009 requirements.

C. Fracture Toughness and Crack Growth Rate Distributions

Sample size requirements are difficult to define because the necessary sample size to characterize an input variable depends on the sensitivity of the RDTA to that variable, the required component reliability and confidence level, and the underlying population distribution of the variable. These recommendations are intended as reasonable starting points for data collection. However, data collection for a reliability analysis is an iterative process which often requires collecting additional data to increase confidence in the input distributions after performing preliminary analysis and sensitivity studies.

1. Crack Growth Rate

When the crack growth rate is modeled as a random variable in the RDTA, at least 6 crack growth specimens should be tested using standard test methods such as ASTM E647 [10]. The specimens should be split among at least 3 material lots.

A minimum of 3 material lots are recommended because the between-lot variance cannot be calculated with fewer than 3 lots.

The crack growth rate is a unique input in the RTDA because it represents a continuous relationship between the stress intensity factor range and the crack extension per cycle, described by multiple related parameters. One example is the NASGRO Equation:

$$\frac{da}{dN} = C\left[\left(\frac{1-f}{1-R}\Delta K\right)\right]^{n} \frac{\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^{p}}{\left(1-\frac{K_{max}}{K_c}\right)^{q}}$$

Uncertainty in the parameters of the crack growth rate model should be quantified using the crack growth rate test results. Methods such as maximum likelihood optimization or Bayesian model calibration may be used.

Testing multiple material lots is recommended because variation in material properties between lots may be larger than variation within lots.

Considering correlations between the equation parameters is important. For example, testing 6 specimens does not produce 6 independent observations of C and 6 of n. Rather, it produces 6 observations of pairs (C, n). Fitting independent distributions for C and n based on a sample size of 6 for each will result in overconfident predictions and unconservative reliability calculations.

2. Threshold Stress Intensity Factor Range

When the stress intensity factor range is modeled as a random variable in the RDTA, the distribution should be characterized by test. The same specimens used to characterize the crack growth rate distribution may be used to characterize the threshold following ASTM E647.

The threshold stress intensity factor range ΔK_{th} is the stress intensity range below which no measurable crack growth occurs. This value is important to a crack growth analysis when the initial flaw size is small, and/or the load spectra include many low amplitude cycles.

3. Fracture Toughness and Strength Properties

When strength and fracture toughness are modeled as random variables in the RDTA, distributions should be characterized by test using standard test methods such as ASTM E399 and ASTM E1820 [11, 12]. Test specimens should be split among at least 3 material lots.

For problems where leakage is the more critical failure case than fracture, fracture toughness and strength may have little influence on the results. Less testing may be required if sensitivity studies are performed to show that the results are not sensitive to these variables.

D. Loads and Environments

When loads are treated deterministically, standard methods of dynamic loads analysis and propulsion analysis should be used to determine the P99/C90 limit load and/or maximum expected operating pressure. Loads in the RDTA should be at limit load level.

Recommendations for modeling loads as probabilistic random variables follow:

1. Uncertainty in vibration and acoustic environments should be characterized through ground testing and flight data
2. Uncertainty in structural dynamic loading should be characterized through simulations, ground testing, and flight data

As an example, the following method may be considered to develop cyclic stress distributions from random vibration and acoustic environment data:

1. Record the vibration and/or acoustic environments local to the component evaluated by RTDA during ground tests and/or flights.
2. Perform a random response analysis of the hardware using each of the recorded environments
3. Evaluate the RMS stress and apparent frequency at the location of interest on the component for each random response analysis.
4. Fit a joint distribution to the RMS stress and apparent frequency pair generated by the random response analysis.
5. Characterize the epistemic uncertainty in the joint distribution parameters based on the sample size (i.e., number of tests or flights)

E. Distribution Fitting Guidelines

Verifications of each input variable distribution should be performed to build confidence in the distributions. These verifications should include goodness of fit tests such as the Anderson-Darling test, plots of the distribution probability density function (PDF) against a histogram of the sample data, and plots of the distribution cumulative density function (CDF) against the sample empirical CDF.

Justification should be documented for the representation (e.g., normal, log-normal, Weibull, or non-parametric representation) for each random variable and may include physical reasoning about the process generating the distribution.

Epistemic uncertainty in the distribution fit to each input variable should be characterized. At a minimum, the uncertainty in distribution parameters due to the sample size (i.e., sampling error) should be quantified. Other sources of epistemic uncertainty which may be considered include the existence of multiple populations and the shape of the distribution tails if there is not sufficient data to characterize them.

IV. Uncertainty Propagation Guidelines

The uncertainty propagation method describes the procedure used to translate the uncertainty in the input variables to the uncertainty in the quantity of interest, in this case the safe life. One example of uncertainty propagation is a Monte

Carlo analysis which samples from the input variable distributions, passes those inputs through a crack growth analysis, and builds a distribution of the resulting life.

A. Aleatory and Epistemic Uncertainty Separation

Aleatory uncertainty is the true underlying variability in a quantity, such as build-to-build geometric variability or variation in fracture toughness. Epistemic uncertainty results from a lack of knowledge or data, such as uncertainty in distribution parameters due to small sample sizes. Epistemic uncertainty may be reduced by collecting additional data or knowledge about a system which aleatory uncertainty is irreducible.

The uncertainty propagation method used to determine the uncertainty in life should maintain separation between aleatory and epistemic uncertainty [13].

Maintaining separation between these types of uncertainty allows the analyst to determine if the calculated life or reliability could be improved by collecting additional data, or if the component is unable to meet reliability requirements and must be redesigned.

One method of maintaining separation between types of uncertainty is a two-level Monte Carlo analysis. The inner loop samples from the input variable distributions and calculates the reliability. The outer loop varies the distributions themselves based on the epistemic uncertainty such that each run of the inner loop uses modified distributions and calculates a different reliability. Parameters modeled as epistemic intervals are also varied in the outer loop. The spread in reliability estimates indicates the epistemic uncertainty while the reliability values indicate the aleatory uncertainty.

B. Sensitivity Studies

Sensitivity studies should be performed as needed to meet the reliability requirement. One method is to individually vary the aleatory and epistemic uncertainty of each input variable while keeping the other variables constant.

The intent of this type of study is to determine which input variables have the largest effect on the reliability and which distributions need better characterization to reduce the output uncertainty.

The type of distribution used to model the most sensitive input variables should be varied in sensitivity studies if the best fit distribution is not confidently known.

The intent of this type of study is to determine how sensitive the reliability estimate is to the assumed choice of distribution. If the reliability is unacceptably sensitive to the distribution type, more data is needed to increase confidence in the distribution type.

V. Additional Considerations

A. Fatigue and Damage Considerations

When the initial flaw size distribution is characterized using hardware which has not been flown, the distribution will only include flaws which exist in the component prior to full integration, transportation, and service. Flaws may initiate during these operations due to fatigue, mishandling, and corrosion. Although these events happen after the final inspections, DDTA provides some protection against these flaws by demonstrating the component is tolerant to relatively large flaws. Components designed to meet RDTA requirements may not tolerate flaws as large and require additional protections.

During component qualification, verification of fatigue life should be performed to show the component has sufficient durability to mitigate the possibility of flaws initiating during service. One component should be fatigue tested to 4 times the service life of the component. The applied load amplitudes and durations should be at the P99/C90 level.

B. Additional Sources of Uncertainty Not Covered by These Guidelines

Other sources of errors in the RTDA include uncertainty in local stress predictions, temperatures, residual stresses, stress intensity factor calculations, and crack growth rate interpolation error.

C. Predicting Low Probabilities of Failure

Individual component-level probabilities of failure may be very small depending on the application. Estimating small probabilities of failure can be challenging. Using sampling-based methods, more samples are needed the lower the probability of failure is. Generally, the number of aleatory samples should be chosen such failure is predicted in 10 – 100 samples. This is further multiplied by the number of samples in the epistemic loop. The total required number of samples can easily exceed 100,000,000 which may be computationally expensive. Strategies such as importance sampling and surrogate modeling can alleviate but not eliminate this difficulty while adding additional complexity to the analysis.

In addition, when the probability of failure is low, failure may require several random variables to be in the tails of their distributions (e.g., very large initial flaw, low fracture toughness, and high loads). Depending on the sample sizes used to characterize these distributions, there may be large epistemic uncertainty in the tail probabilities. This can make it challenging to meet the reliability requirement with an appropriate confidence level.

D. Using Deterministic Values in Reliability Analysis

Using deterministic upper / lower bound values in the RDTA can distort the calculate reliability. In this paper, reference is made to deterministic upper bound flaw sizes, worst-case geometry, P99/C90 loads, and A-basis lower bound material properties. When deterministic values are used in the RDTA, whether the calculated reliability is conservative or unconservative depends on the shape of the distribution tail beyond the chosen bounding value and the analysis sensitivity to that variable.

For example, if deterministic loads at the 99th percentile (i.e., P99/C90) are used, the RDTA may show a near 100% reliability. However, loads at the 99.5th percentile could be much higher than P99/C90 loads and consistently cause failure, indicating the true reliability is no higher than 99.5%. For this reason, it is recommended to treat as many variables as probabilistic as is practical in the RDTA.

E. Importance of Process Controls

The calculated reliability from the RDTA is tied to the specific distributions of initial flaw size, geometry, material properties etc. used in the RDTA. Deliberate changes which affect these distributions, such as changing suppliers or tooling, can invalidate the RDTA result. After deliberate process changes, checks should be performed to verify that the new hardware is in-family with the previous hardware, or the RDTA should be updated considering the new process. Unintended changes such as process drift can invalidate the RDTA results as well and should controlled.

VI. Summary

Guidelines were proposed for performing a reliability-based damage tolerance analysis of launch and space vehicle structures. These guidelines cover damage tolerance analysis ranging from fully deterministic to fully probabilistic. These proposed guidelines are put forth to accelerate adoption of these methods in the risk characterization and design certification of space vehicle components. This work is a starting point for discussions at future workshops intended to develop an industry consensus on how reliability-based approaches can be incorporated into damage tolerance assessments.

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