Langley Research Center

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WIND-TUNNEL MODEL SYSTEMS CRITERIA

National Aeronautics and Space Administration

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PREFACE

Purpose

This procedure and guideline sets forth criteria for the design, analysis, quality assurance, and documentation of wind-tunnel model systems to be tested at the Langley Research Center (LaRC). The criteria contained in this directive are intended to prevent model system failure and/or facility damage. The requirements in this directive are mandatory for model systems to be tested in the specified closed-circuit wind tunnels and may become mandatory (wholly or in part) for model systems in other facilities, to the extent established by the Executive Safety Board (CID 1150.2, "Boards, Panels, Committees, Councils, and Teams").

Applicability

This directive is applicable to all civil servants at Langley Research Center.

Authority

1. 42 U.S.C. 2473 (c)(1), Section 203 (c)(1) of the National Aeronautics and Space Act of 1958, as amended.

References

1. CID 1150.2, "Boards, Panels, Committees, Councils, and Teams."

2. LPR 1710.40, "Safety Regulations Covering Pressurized Systems."

3. LPR 1740.4, "Facility System Safety Analysis and Configuration Management."

4. LPR 7320.1, "Engineering Drawing System."

5. LMS-CP-4505, "Prepare Purchase Request (PR) and Supporting Documents."

6. CID 5640, "Requesting, Performing, and Closing Fabrication Services Requests."

7. Langley Form (LF) 136, "Fabrication and Inspection Operations Sheets."

8. LF 143, "Nonconformance Failure Report."

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Cancellation

LAPG 1710.15, dated September 27, 2000, is superseded and should be destroyed.

original signed on file

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DISTRUBUTION
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CHAPTER 1

APPLICABILITY AND IMPLEMENTATION

1.1 INTRODUCTION

This guide contains criteria for the design, analysis, quality assurance, and documentation of wind-tunnel model systems to be tested in the specified wind tunnels at Langley Research Center (LaRC). The guide also applies to models under the control of LaRC that will be tested at the Wallops Flight Center and at the Dryden Flight Research Center (these facilities may require criteria in addition to this document). The criteria are intended to prevent model system loss and/or potential facility damage.

1.2 APPLICABILITY

The requirements in this document are mandatory for model systems to be tested in the following tunnels:

Low-Turbulence Pressure Tunnel
Transonic Dynamics Tunnel
16-Foot Transonic Tunnel
14 X 22 Foot Subsonic Tunnel
National Transonic Facility
0.3-Meter Transonic Cryogenic Tunnel
20-Inch Supersonic Wind Tunnel
Unitary Wind Tunnel
8-Foot High Temperature Tunnel

In addition, drop model systems and remotely piloted vehicle systems (RPVs) shall comply with the requirements of this document.

The requirements of this guide or portions thereof may become mandatory for model systems to be tested in other wind tunnels at LaRC, to the extent established by the Executive Safety Board (see CID 1150.2, "Boards, Panels, Committees, Councils and Teams").

1.3 DEFINITIONS

a. **Catastrophic**: A failure that may cause death, permanent disability, the hospitalization of three or more people, and/or system/equipment damage in excess of $250,000 (Type A or B Mishap).
b. **Critical**: A failure that may cause lost time injury or illness, and/or system/equipment damage between $25,000 and $250,000 (Type C Mishap).
c. **Critical Speed:** A speed of a rotating system that corresponds to a resonant frequency of the system.

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d. **Critically Loaded/Stressed Component:** For metals, a component that is vital to the structural integrity or whose factor of safety is less than the allowable for a Method 1 (Section 2.6b) analysis. For nonmetals, the TPE, MSE, TE, or FSH will review each component for criticality on a case-by-case basis.
e. **Facility Safety Head (FSH):** The person responsible for the safe operation of the facility. The FSH represents the final approval authority for all models to be tested in the facility. (FSH's are listed in the LaRC Telephone Directory.)
f. **Force Measurement Engineer (FME):** The engineer assigned the overall responsibility for the design, fabrication, and maintenance of the force balance used as a part of the model system.
g. **Formal Engineering Design Review:** A review of the model system design by a panel composed of representatives of pertinent organizations (engineering, model safety, research, research facility, instrumentation, fabrication, quality assurance, and so forth). Recommendations from this panel shall be documented and forwarded to the TPE/RPE/TE for disposition.
h. **Informal Engineering Review:** A review of the engineering design by personnel other than those directly involved in the model design.
i. **Lead Technician:** The fabrication technician assigned fabrication planning and coordination responsibility for the model system.
j. **Mandatory Facility:** A wind tunnel facility that shall abide by the criteria established by this document.
k. **Model Systems:** Model systems covered by this handbook are defined as models, flow survey devices, splitter plates, model support hardware including force balances (Section 2.14 only), and stings.
   (1) **Exclusions:** This handbook does not apply to the following:
      (a) Model support equipment that is a permanent part of the facility.
      (b) Off-the-shelf components such as gearboxes, motors, actuators, instrumentation mounts, and so forth, which are not critical to the structural integrity of the model system and whose failure cannot result in facility damage.
      (c) Ancillary equipment such as arc sectors, cables, brakes, and foundations that are not a part of the model itself.
l. **Model ~~Systems~~Safety Engineer (MSE):** The MSE serves as the resident expert for the review of model systems design and analysis. The MSE also serves as the point of contact to assist the FSH in interpreting the requirements for compliance with this handbook.
m. **Planning Meeting:** A pre-design meeting usually involving research, facility, design, and instrumentation personnel with a prime objective establishing the model systems requirements and the applicability of this handbook.
n. **Pretest Meeting:** A meeting usually involving research facility, design, instrumentation, and, as applicable, user personnel with the objectives of establishing the test plan, recognizing test constraints and ensuring model readiness.
o. **Quality Assurance Specialist (QAS):** The specialist assigned to support the implementation of the quality assurance requirements.
p. **Research Project Engineer (RPE):** The research organization cognizant engineer assigned the responsibility for configuration definition and testing of the model system. The RPE shall coordinate activities with the TE.

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q. **Test Engineer (TE):** The resident engineer at the test facility that has been assigned the test on the model/system under consideration.
r. **Technical Project Engineer (TPE):** The cognizant engineer assigned the overall responsibility for the design and fabrication of the model system.
s. **User-Furnished Model System:** Model system that is designed and fabricated without NASA-LaRC design review and manufacturing control.

1.4 IMPLEMENTATION

a. The FSH has the responsibility and authority to implement the criteria in this guide. For all in-house and user furnished model systems being tested in a mandatory facility as described in Section 1.2 Applicability, the FSH shall be assisted by a MSE. For other matters, the FSH may elect to be assisted by an MSE.
b. The TPE/RPE/TE has the responsibility of ensuring that the model system design meets the criteria of this guide. Any deviations to these criteria are to be addressed according to the deviation procedure given in Chapter 6.
c. The MSE shall review any structural modifications that affect the safety of the model. This requirement applies to a model being tested in a mandatory facility as described in Section 1.2. The FSH shall determine the need for this review.

1.5 REVIEWS

a. Model system reviews are to be conducted to help ensure that the systems are functional, meet the research requirements, and meet the criteria set forth in this guide.
b. Planning meetings, pretest meetings and informal engineering reviews are mandatory for model systems covered by this guide. These reviews may be combined provided the objectives set forth in this guide are addressed.
c. Formal engineering design reviews may be required for those designs that are especially complicated, potentially hazardous to LaRC facilities, or require a number of deviations. The FSH, TPE, RPE, TE, or MSE can request a formal engineering review.

1.6 ADDITIONAL REQUIREMENTS

Requirements beyond those specified in this guide may be imposed. The FSH is authorized to implement additional requirements as necessary.

1.7 WIND TUNNEL MODEL SYSTEMS COMMITTEE

The Wind Tunnel Model Systems Committee, as outlined in CID 1150.2, "Boards, Panels, Committees, Councils and Teams", has ownership of this document. All requests for additions, deletions, and changes should be forwarded to the chairman of this committee.

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CHAPTER 2

DESIGN AND ANALYSIS

2. 1 GENERAL

a. **Design Loads:** The design loads data are to be established by research personnel and must be consistent with safe operating limits of the facility. The design loads data shall be a part of the Model Systems Report (see Chapter 5).
b. **Documentation:** The documentation shall include, where applicable, aerodynamic and thermal loads for the extremes of the test condition model configurations, design cycle life requirements, and inertia driving forces and frequencies for dynamic and transient testing.
c. **Critically Loaded/Stressed Components**: A list of all critically loaded/stressed components, including fasteners, shall be generated and included in the Model Systems Report. The worst-case impact on the facility if component failure occurs shall be identified for each component. For example, if a particular component fails, will small debris fly down the tunnel and be stopped by a screen or will the whole model fly down the tunnel and result in catastrophic facility damage. When identifying impact on the facility, the secondary effects of the failure must be considered. For example, a component failure may not directly result in facility damage, but the secondary effects (e.g., increased aerodynamic loads or unbalanced rotary system) may result in additional component failures that result in facility damage.

2.2 STANDARDS

Unless otherwise specified, applicable provisions of the following standards, codes, or handbooks are acceptable:

a. American National Standards Institute (ANSI)
b. American Institute of Steel Construction (AISC)
c. American Society for Testing Materials (ASTM)
d. American Welding Society (AWS)
e. American Society for Nondestructive Testing (ASNT)
f. American Society of Mechanical Engineers (ASME)
g. National Electric Code (NEC)
h. National Design Specification for Stress Grade Lumber (NDSSGL)
i. Society of Automotive Engineers (SAE)
j. LPR 1710.40, "Safety Regulations Covering Pressurized Systems"
k. National Institute of Standards and Technology (NIST)
1. Aerospace Structural Metals Handbook--Department of Defense (DOD)
m. Advanced Composite Design Guide--DOD/NASA
n. Systems Engineering Division Bolted Joint Handbook (SED EHB-2)

Unless identified by date, the edition—including addenda and code cases—in effect at the start of the design, is to apply.

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2.3 MATERIAL SELECTION

a. **Standards:** Materials shall be selected using mechanical or other physical properties from experimental test data or the latest issue of recognized standards. Minimum properties, when available, shall be used rather than nominal or typical properties.

b. **Adjustments:** All material properties, design criteria, and allowable stresses, are to be suitably adjusted for test temperature, pressure, stress corrosion, and any other environmental effects which may be present during the period the material is under stress.

c. **Material Properties Verification:** Materials used for critically stressed components or those materials subject to nonstandard or special processing are to have as-built properties verified at test temperature. In particular, for cryogenic applications, tensile and fracture toughness tests shall be performed to measure strength and toughness against expected values.

d. **Galling:** Galling shall be considered in material selection.

e. **Fracture Toughness:** For all cryogenic models and for other applications requiring high material toughness, the fracture toughness (K_{Ic}) properties set forth in this section are required for critically stressed components. The material must have a documented K_{Ic}, fracture toughness, value that exceeds 65 ksi (in.)$^{-}$ at the operating temperature. Acceptable documentation will include K_{Ic} test data on the material obtained by the manufacturer using the ASTM standard test procedure E399. If the manufacturer does not have K_{Ic} test data available, published test data available in the literature may be used if the heat treat, material chemistry and test temperature are similar to the operating condition. This literature data must include two independent sources of data and be from a reputable resource such as those defined in Section 2.3f. However, alloys with fracture toughness values less than 65 ksi (in.)$^{-}$ may be acceptable provided that the fracture mechanics analysis performed according to Section 2.4d proves that the design life is adequate.

f. **Cryogenic Model Systems:** In selecting materials for cryogenic application, special consideration must be given to low temperature embrittlement, coefficient of thermal expansion, and dimensional stability. Such consideration must be given not only to primary (load carrying) structural materials but also to solders, brazes, fillers, and so forth.

   (1) **Cryogenic Materials Data Sources:** Suggested sources of information on materials that have been characterized and evaluated for cryogenic uses are as follows:

      (a) Materials for Cryogenic Wind Tunnel Testing. National Bureau of Standards Report, NBSIR 79-1624, May 1980.

      (b) Cryogenic Materials Data Handbook. Volumes I and II. Technical Documentary Report, AFML-TDR-64-280 (Rev. 1970).

      (c) Handbook on Materials for Superconducting Machinery. Metals and Ceramics Information Agency Report, MCIC-HB-04, November 1974.

      (d) Fastener Load Tests and Retention Systems for Cryogenic Wind Tunnel Models. NASA TM 85805, 1984.

      (e) Materials and Techniques for Model Construction. NASA CR 172620, June 1985.

      (f) Cryogenic Model Materials, AIAA-2001-0757, 2001

2.4 STRUCTURAL ANALYSIS

a. **Stress Analysis:** A stress analysis is required as a part of the Model Systems Report (see Chapter 5). It is to be complete and sufficiently comprehensive to require no further explanation.

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(1) The stress analysis is to show that allowable stresses are not exceeded for the worst load case(s).
(2) Each detailed analysis section shall identify load paths, contain a sketch showing forces and moments acting on the part (free body diagram) and include statements of assumptions, approximations, section and physical properties, type and heat treat condition of the material, and pertinent drawing number.
(3) The general equations and their sources are to be given before substitution of numerical values.
(4) Section properties for shear, axial, bending, and torsion of structural members shall be defined at an adequate number of stations to facilitate a check on the location of the designated critical sections.
(5) Finite element analyses documentation shall include computer generated plot(s) of the finite element model(s), tabular or graphical summary of stress data, and name of structural code used. Validation of finite element model(s) is required by either closed form solution approximations or other evidence that shows high confidence in the finite element model(s) such as equilibrium checks, convergence accuracy of solution, and so forth.
(6) Dimensional tolerances, potential model installation errors, and potential local flow conditions must be considered when determining loads on model components. If, for the analysis of all parts with lifting surfaces (vertical stabilizers, pylons, and struts, and so forth) which are normally intended to be aerodynamically unloaded, the above misalignments are determined to be less than +/-1 degree, then a misalignment of at least +/-1 degree with respect to the freestream must be used.
(7) Loads caused by pressure differences due to unvented cavities must be considered.

b. **Thermal Analysis:** Sufficient analysis shall be performed to examine thermal stresses and distortions for steady state and transient conditions.

c. **Fatigue Analysis:** The provisions of this section apply to components that are subjected to cyclic loadings to the extent that fatigue is a credible failure mode. The fatigue analysis is performed on the premise that no flaws or cracks initially exist in the structure. In general, good practice for designing fatigue resistant structures is expected to be followed such as: proper material selection, keeping stress concentrations to a minimum by avoiding sharp discontinuities and using generous radii, and so forth. Appendix A is provided as a guide for performing fatigue design analysis and for determining the allowable oscillating stress based on model system design life requirements.

d. **Fracture Analysis:** A fracture mechanics analysis is mandatory for critically stressed components and all cryogenic model system components. The fracture analysis precludes the fatigue analysis as the basis for design life calculations for cryogenic model systems. Figure 1 is a flowchart that guides the designer through the criteria needed to satisfy the fracture requirements. Details regarding performing a fracture analysis are provided in Appendix B. Three levels of analysis are presented in Appendix B, which will satisfy the fracture analysis criteria as described in this document.

e. **Design Life:** The RPE/TE shall specify the design life requirements for the fatigue and/or fracture analysis for model system components. (See Section 2.10e for special fatigue life requirements for rotating model system components.) In cases where the projected load-cycle/design life requirement is not well defined, the following approximations may be used:

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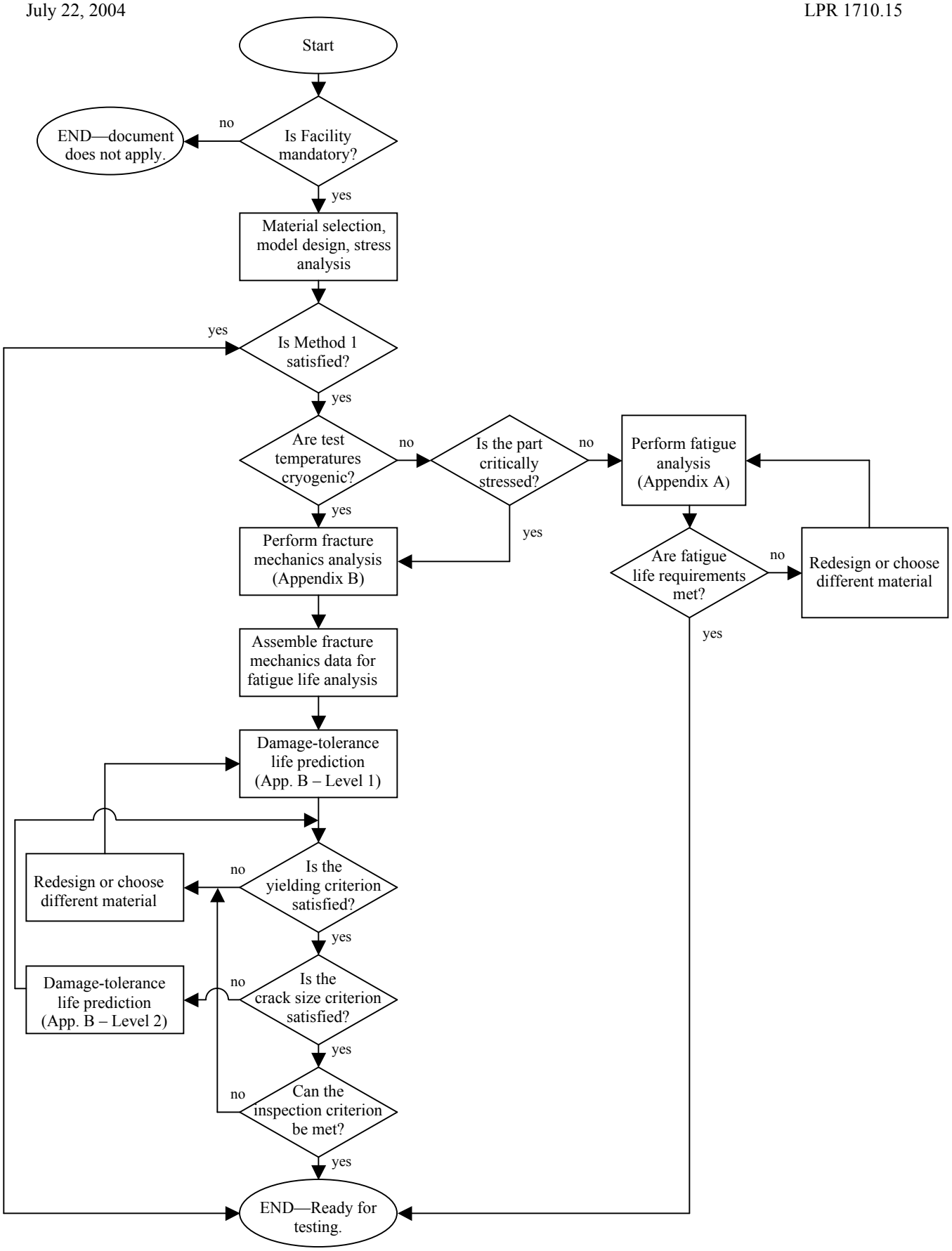

Figure 1 – Flowchart used to determine which criteria is needed to satisfy fracture requirements.

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(1) **Peak Load Cycles:** Estimate the number of times the model system component will experience maximum steady-state load conditions over the test life and multiply this number by three. Use this number as the primary design life-cycle requirement.

(2) **Unsteady Oscillating Loads:** For purposes of estimating the magnitude of the unsteady cyclic loads, assume the maximum peak unsteady load to be at least 25 percent of the steady load. This does not apply to unsteady aerodynamics test models. Generally, the unsteady loads result in less fatigue damage as opposed to peak load cycles. However, for wind tunnel models, there is no statistical database for predicting unsteady loads as they are usually model and/or tunnel dependent. In cases where significant unsteady loads (>50 percent of steady-state) may be possible, then on-line monitoring of dynamic loads shall be required. Once an unsteady load history is established during testing, the design shall be reevaluated for fatigue life.

2.5 MECHANICAL CONNECTIONS

a. **Structural Joints:**

(1) **Welded Joints:** All welded joints not associated with pressurize systems are to be designed and fabricated in compliance with AWS, ASME, or AISC standards. Both the weld and the structure near the weld are subject to the stress criteria set forth in Section 2.6, with appropriate adjustment for the effects of the welding process (for example, strength reduction in the heat affected areas).

(2) **Bolted Joints:** Bolted joint design shall satisfy the allowable stress criteria as set forth in Section 2.6b and may require independent evaluations of the strength of the joining components, particularly if dissimilar materials are involved. All components of bolted joints shall be designed to account for the relative elasticity of the joint members and to account for any prying action produced by deformations of the joint. (See Section 2.5b)

b. **Threaded Fasteners:**

(1) In general, the length of thread engagement should be at least 1.5 times the nominal diameter of the fastener. If less thread engagement is used, the minimum shear strength of the threads in the joint shall be at least 4/3 times the bolt preload.

(2) Bolted joints should not rely on friction to transmit loads or maintain necessary alignments. In a joint without keys, pins, or shoulders, the weakest bolt (considering material and size) in the joint shall be sized to carry the entire joint shear load and shall meet the allowable shear stress criteria as specified in Section 2.6b. If the joints are subject to larger than allowable shear forces, then keys, pins, shoulders, and so forth shall be used to transmit the shear loads and maintain alignment.

(3) Preloads: Threaded fasteners shall be torqued to produce a preload equivalent to 75 percent of the yield strength of the fastener unless a lower preload is required due to thermal or mechanical considerations. The preload shall provide a clamping force of at least 1.5 times the maximum expected separating force in any of the fasteners.

(4) Factor of Safety: The factor of safety for the fasteners is the appropriate load rating for the fastener, in accordance with Section 2.6b, divided by the external load for the fastener, and must be greater than or equal to 4 on ultimate and 3 on yield.

(5) Retention: In addition to torquing to prescribed preloads, threaded fasteners shall also be secured by mechanical systems (that is, locking-tab washers, locking inserts, interference threads forms, safety wiring, and so forth) and/or chemical locking systems (that is, thread-locking adhesives, fillers, and so forth). Thread-locking systems that do not affect

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installation torques are preferred. Torque to 75% of the yield strength (as in (3)) is considered to be one locking method.

2.6 METALLIC MATERIALS ALLOWABLE STRESS

a. **General:** The allowable stress criteria for metallic materials given in this section are based on well established design practices. Three methods are provided for establishing stress design allowables. Methods 1 and IA are based on conventional conservative approaches, which can be employed, where structural design optimization is not a factor, and minimum analysis effort is needed. Method 2 is a systematic approach, which can yield a more optimum structural design. Individual structural components or subsystems can be designed to the allowable of either Methods 1, 1A, or 2 in combination as long as the analysis requirements are met for each method. More simply stated, this means that some parts of the model system may be designed to the allowables of Methods 1 or 1A while other parts may be designed to the allowables of Method 2.

b. **Method 1:** For standard handbook analysis, the allowable compound stress (axial plus bending) is the smaller of the values of 1/4 of the minimum ultimate strength or 1/3 of the minimum yield strength of the material. This corresponds to a safety factor of 4 on ultimate or 3 on yield, respectively. In this method, the compound stress to be compared to the allowable shall be calculated for worse combined load cases (mechanical plus thermal) and include stress concentration effects. If published shear strengths are available, allowable shear stresses shall meet the preceding safety factor requirements with respect to shear ultimate and yield strengths. In the absence of shear strength data, the maximum allowable shear yield stress for all combined loads will be taken as 1/2 of the minimum tensile yield strength, consistent with the Maximum Shear Stress Theory of Failure, with a required safety factor of 3. When using the von Mises stress theory, the maximum allowable shear stress is equal to $\hat{o}_{allow} = S_y / \sqrt{3}$, consistent with the von Mises failure theory, with a required safety factor of 3.

c. **Method 1A:** In certain cases, at the discretion of the design engineer, and approved by the TPE/RPE/TE, a variation on the allowables of Method 1 is acceptable. Method IA is intended to address situations where the allowables of Method 1 cannot be met by including stress concentration effects in areas where the stress state is well defined (for example, a model sting loaded in bending with a small hole in it). In such cases, a highly localized stress cannot result in collapse of the structure but rather becomes a concern in terms of localized distortion and crack initiation, which could lead to fatigue failure. In such cases, the allowables of Method 1 may be used without including the stress concentration effect. However, the stress concentration effect along with other fatigue reduction/modification factors must be applied to show that fatigue failure is not a problem by performing a fatigue or fracture analysis as per Section 2.4c or 2.4d, respectively.

d. **Method 2:** This method can be used when the system cannot be designed to the allowables of Methods 1 or 1A. However, in order to design to the allowables in this section, the stress state in the model system structure must be well understood to a high level of confidence. Closed-form solutions and standard handbook calculations will in many cases suffice. All contributions to stress shall be included in the calculations. However, for highly

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indeterminate complex structures, more in-depth analysis will be required using state-of-the-art structural analysis codes employing finite-element or finite-difference techniques.

(1) The first type of theory available for a Method 2 analysis is based on the **ASME Boiler and Pressure Vessel Code, Section VIII, Division 2**

(a) **Stress Terminology**

(1) **Combined Principal Stress Intensity:** The combined Principal stress intensity is defined as twice the maximum shear stress and is the difference between the algebraically largest principal stress and the algebraically smallest principal stress at a given point.

(2) **Normal Stress:** The stress normal to the plane of reference.

(3) **Shear Stress:** The stress tangent to the plane of reference.

(4) **Membrane Stress:** The component of normal stress, which is uniformly distributed and equal to the average value of stress across the thickness of the section under consideration.

(5) **Primary Stress:** The stress (normal or shear) which is necessary to satisfy the simple laws of equilibrium of external and internal loads. A thermal stress is not a primary stress. Examples of primary stresses are: general membrane stress (axial force divided by gross cross-sectional area of a structural element) and bending stress (bending moment divided by the section modulus of a structural member).

(6) **Secondary Stress:** The stress (normal or shear) developed by constraints or by the self-constraint of a structure. Examples of secondary stresses are: general thermal stress and bending stress at a gross structural discontinuity (sudden changes in geometry).

(7) **Incremental Peak Stress:** Incremental peak stress is defined as the increment added to the stress at a point to give the total peak stress in areas of stress concentrations. The basic characteristic of a peak stress is that it does not cause any noticeable distortion and is objectionable only as a possible source of a fatigue crack or a brittle fracture.

(8) **Thermal Stress:** Thermal stress is a self-balancing stress produced by a nonuniform distribution of temperature or by differing coefficients of thermal expansion. Two types of thermal stresses are considered: general thermal stress associated with distortion of the structure in which it occurs and local thermal stress associated with almost complete suppression of the differential expansion/contraction and thus produces no distortions. Such stresses shall be considered only for fatigue design.

(9) **Stress Cycle:** Stress cycle is a condition in which the alternating stress difference goes from an initial value through an algebraic maximum value and an algebraic minimum value and then returns to the initial value. A single operational cycle may result in one or more stress cycles.

(b) **Calculation of Combined Principal Stress Intensity:** At the point on the structure, which is being investigated, choose an orthogonal set of coordinates (i,j,k). The stress components in the directions are then designated σ_i, σ_j, σ_k for normal stresses and τ_j, τ_k, τ_{ki} for shear stresses.

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Calculate the stress components for each type of loading to which the part will be subjected and assign each set of stress values to one or a group of the following categories.

(1) General primary membrane stress, σ_m
(2) Primary bending stress, σ_b
(3) Secondary stress, σ_s
(4) Incremental peak stress, σ_p

Translate the stress components in the [i,j,k] (may be rectangular, cylindrical, or spherical coordinates) directions into principal stresses σ_1, σ_2, σ_3. Next calculate the absolute value of the stress difference σ_{12}, σ_{23}, σ_{31} from the relations:

$\sigma_{12} = abs(\sigma_1 - \sigma_2)$ **NOTE:** For a biaxial state of stress $\sigma_3 = 0$.
$\sigma_{23} = abs(\sigma_2 - \sigma_3)$
$\sigma_{31} = abs(\sigma_3 - \sigma_1)$

The combined principal stress intensity S is the largest (absolute value) of σ_{12}, σ_{23}, σ_{31}.

(c) **Combined Stress Intensity Allowables:**

(1) General Primary Membrane Stress Intensity, σ_m, shall not exceed the allowable membrane stress, S_m. S_m will be the smaller of:

$$\tfrac{1}{2} F_1 * S_y \text{ or } \tfrac{1}{3} S_u$$

where

S_y = minimum specified yield strength
S_u = minimum specified ultimate strength

and

$$F_1 = (.8)[2 - S_y / S_u], \text{ but always } <= 1.0$$

For the austenitic stainless steels and all nickel alloys with stress-strain behavior similar to the austenitic steels, S_m, can be taken to the smaller of:

$$\tfrac{2}{3} S_y \text{ or } \tfrac{1}{3} S_u$$

(2) Primary membrane plus primary bending stress intensity, $\sigma_m + \sigma_b$, shall not exceed 1.5 times S_m, that is,

$$\sigma_m + \sigma_b \leq 1.5 S_m$$

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(3) Primary plus secondary stress, shall not exceed 2.0 times S_m,

$$\sigma_m + \sigma_b + \sigma_s \leq 2.0 S_m$$

(4) Primary plus secondary plus incremental peak stress intensity shall not exceed the allowable alternating stress, S_a, as established by Fatigue Analysis (see Section 2.4c).

$$\sigma_m + \sigma_b + \sigma_s + \sigma_p \leq S_a$$

The allowable stresses are summarized in the following table:

Combined Stress Intensity (2)	Tabulated Value	Yield		Ultimate	
		Most Metals	Austenitic SS and Nickel Alloys	Most Metals	Austenitic SS and Nickel Alloys
σ_m	S_m	$^1/_2\ S_y$	$^2/_3\ S_y$	$^1/_3\ S_u$	$^1/_3\ S_u$
$\sigma_m+\sigma_b$	$1.5\ S_m$	$^3/_4\ S_y$	S_y	$^1/_2\ S_u$	$^1/_2\ S_u$
$\sigma_m+\sigma_b+\sigma_s$	$2.0\ S_m$	S_y	$^4/_3\ S_y$	$^2/_3\ S_u$	$^2/_3\ S_u$
$\sigma_m+\sigma_b+\sigma_s+\sigma_p$	S_a	…	…	…	…

(2) The second type of theory available for a Method 2 analysis is the **von Mises Theory,** which is the same as the **Maximum Distortion-Energy Theory** and the **Octahedral Shear Stress Theory**. The von Mises stress represents all of the stresses present in an element (σ_x, σ_y, σ_z, σ_{xy}, σ_{xz}, σ_{yz}) as a single stress. This stress can then be compared to the yield strength or the ultimate strength of the material. Most finite element programs are capable of generating maximum von Mises stresses.

(a) **Tri-Axial Stress State:**
For stress states where there are normal stresses in the 1, 2 and 3 directions, the shearing stress is:

$$\tau_{oct} = \frac{\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}}{3}$$

Also,

$$\tau_{oct} = \frac{\sigma_e}{3}\sqrt{2}$$

Then, the von Mises equivalent stress becomes:

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$$\sigma_e = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}{2}}$$

(b) **Bi-Axial Stress State:**
For stress states where there is a stress in the 1 direction, the 2 direction and a shear stress, the von Mises equivalent stress is:

$$\sigma_e = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2 + 3\tau_s^2}$$

(c) **Single Axis Stress State:**
For a stress state that consists of one normal stress and a shear stress, the von Mises equivalent stress is:

$$\sigma_e = \sqrt{\sigma^2 + 3\tau_s^2}$$

(d) **von Mises Theory Allowables**
The maximum allowable stress shall be:

Calculated Value	Yield Strength		Ultimate Strength	
	Most Metals	Austenitic SS and Nickel Alloys	Most Metals	Austenitic SS and Nickel Alloys
σ_e	S_y	$^4/_3\ S_y$	$^2/_3\ S_u$	$^2/_3\ S_u$

2.7 NONMETALLIC MATERIALS ALLOWABLE STRESS

a. **Composites:** Due to the various criteria available for composite material analysis, the numerous composite materials in use and development, and the lack of complete acceptance of a single failure criterion for all materials, a conservative methodology will be utilized for composite material analysis. The glass- or graphite-based composite materials used for models shall be limited to laminates having quasi-isotropic stacking sequences and shall have a factor of safety of 2.0 on strain limits of 0.003 in/in in the laminate (in-plane and out-of-plane). In other words, the strain shall not exceed 0.0015 in/in. Fatigue analyses using an appropriate and documented criterion must be performed where applicable. If justification exists for utilizing a laminate other than quasi-isotropic and/or design modifications are not possible to meet strain requirements, sufficient analysis and testing utilizing a documented failure criterion shall be required. Design and analysis must address both the effect of environment and the effect of stress concentrations caused by holes or other stiffness discontinuities on the residual strength of the structure. In some cases, structural testing will be necessary in addition to analysis to establish acceptability. In other cases, for example

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designs to structural response targets, structural testing will be necessary in lieu of analysis to establish acceptability of composite components.

b. **Wood:** The orthotropic nature of the mechanical properties of wood as well as environmental effects must be considered when determining allowable stresses. Allowable stresses shall be 1/3 of the minimum strength for the appropriate load type and orientation with respect to the grain.
c. **Glass:** Due to the brittle nature of glass, the allowable stress is 1/10 the material ultimate strength.
d. Other materials shall be dealt with on an individual basis.

2.8 STABILITY

a. **General:** When the model system is to be analyzed for stability, rigid body motions shall be considered about all axes, and flexibility about pitch, roll, and yaw axes shall be considered for aeroelastic stability.
b. **Divergence:** A safety factor of 2 against divergence is required in the analysis and/or system stiffness verification. That is, the divergent dynamic pressure is to be greater than the test dynamic pressure by a factor of 2. This requirement is also satisfied if the ratio of the model/sting normal force increase due to change in angle-of-attack (_N/__) does not exceed 1/2 of the support system restoring force generated by such an angle change (_F/__). This paragraph is not applicable to models that are tested for divergence.
c. **Flutter:** It is expected that the aeroelastic stability of most model systems will be governed by divergence. However, where flutter becomes a design constraint, a safety factor of 2 based on test dynamic pressure shall be required in the analysis. This paragraph is not applicable to models that are tested for flutter.
d. **Dynamics:** Models to be dynamically tested shall be analyzed to show that the mountings and/or emergency restraints are structurally adequate and dynamically stable.
e. **Buckling:** The allowable compressive stress/load in columns and skins using the proper slenderness ratio shall not exceed 1/2 of the critical buckling stress/load.

2.9 PRESSURIZED SYSTEMS

a. All pressurized components, vessels and systems outside of models, or which have the maximum pressure times the maximum projected area of the pressurized surface greater than 7000 pounds, shall be in accordance with LPR 1710.40, "Safety Regulations Covering Pressurized Systems."
b. Relief devices are required in the supply system (but not necessarily in the model) and are to be capable of discharging the full flow of the pressure source under all conditions.
c. Pressure systems inside the model, which have the maximum pressure times the maximum projected area of the pressurized surface less than 7000 pounds, will be designed in accordance with the provisions of this guide. The design working pressures and temperature for these systems can be the local static conditions at selected points within the system.
d. In addition to the design requirements specified in Section 2.9c, pressure testing of pressure systems is required where feasible.
   (1) Hydrostatic testing of pressure systems is the preferred method of pressure testing. Test pressure is to be no less than 1.5 times the design pressure times the ratio of the material strength at hydrostatic test temperature to the material strength at design temperature.

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Hydrostatic testing is potentially hazardous. Adequate safety precautions are to be taken to ensure safety of personnel and equipment with regard to test procedures. Hydrostatic testing must conform to the testing requirements set forth in LPR 1710.40. After testing, components shall be dried appropriately.

(2) Pneumatic testing of pressure systems will be performed only when hydrostatic testing is not feasible. A gas complying with the cleanliness requirements of the system will be used. Pneumatic testing is inherently dangerous and all personnel must be excluded from a predetermined hazard zone. Pneumatic testing must conform to the testing requirements set forth in LPR 1710.40.

2.10 ROTATING SYSTEMS

a. **General:** The special requirements set forth in this section apply to model systems, which have rotating parts such as propellers and/or rotors. A rotor is defined as predominantly providing vehicle lift, while a propeller predominantly provides vehicle thrust. In situations where these definitions are unclear, the FSH will determine the appropriate criteria.

b. **Design for Normal Operation:**

(1) The model system and supporting structure shall be designed such that the natural vibration frequencies are removed from operation point speeds by at least 10 percent unless adequate damping is provided to ensure dynamic stability of the system. Also, the system shall be designed such that the natural frequencies are removed by at least 10 percent from likely excitation frequencies, which may be a fraction, or a multiple of the operating speed. Whenever system resonance cannot be avoided during testing, the system shall be monitored during passage through or operation near resonant (critical) speeds, to assure that the combined static and dynamic loads do not exceed design limits. (See Section 2.10g)

(2) Propeller model drive systems shall be designed to operate at 20 percent overspeed. Rotor model systems shall be designed to operate at 10 percent overspeed.

(3) Fasteners, which are designed to carry loads associated with rotation, must be secured by mechanical locking (see Section 2.5b(5)). Such fasteners shall include not only those securing rotating parts but shall also include all fasteners, which translate rotational loads back to the test bed. For example, fasteners that hold the pylon to the nonrotating parts such as nacelle, and to the model fuselage fall into this category.

(4) Provisions shall be made for balancing the system. (See Section 2.10f)

(5) Bearing life and lubrication requirements must be specified for the expected operating environments.

(6) Particular models may require the consideration of periodic rotational speed loadings. These loadings may result from struts, inlet guide vanes, outlet stators, and so forth.

c. **Design for System Failure Event:** Models shall be designed such that after an initial failure, the model shall not experience any further failure that would cause facility damage during the tunnel shutdown process (that is, ultimate safety factors must be greater than 1.0 when unbalanced loading is considered).

(1) Propeller model system unbalance loads shall be calculated as follows: For an even number of blades, design for loss of 1/2 the total number of blades. For an odd number of blades, design for (N-1)/2 blades being lost, where N is the number of blades.

(2) Rotor model systems shall be designed to sustain the loss of one blade.

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(3) For both propeller and rotor models, particular model configurations may require the consideration of simultaneous blade failure on multiple hubs.
(4) For both propellers and rotors, blade(s) loss is a dynamic (transient) event and amplification of the steady state, unbalanced loads can be expected. In the absence of a transient analysis, a dynamic load factor of two shall be applied to the steady-state unbalance loads.
(5) For propeller model high risk applications (that is, rotating component(s) whose failure would result in model loss and/or damage to tunnel fan), the model propeller drive system shall be designed for positive containment of drive system components, excluding the hub assembly. Positive containment is not required for rotor models.
(6) Whenever appropriate, the effects of bearing failure should be considered.
(7) The requirements of this section are established to protect the facility from secondary model failure due to the forces caused by blade loss or bearing failure. The requirements of this section may, in certain circumstances, be waived under the guidelines established in Chapter 6, "Deviations." A valid rationale for a waiver might be tunnel features which reduce risk (for example, low freestream velocities, tunnel fan placement, catcher screens, and so forth) or by additional certification, testing, and operational procedures relating to the model itself, such as increasing the factors of safety on the blades, performing fatigue analyses, and establishing detailed inspections at set intervals. To increase the probability of approval of the deviation request, the approving authority should be informed as soon as possible that such a request is being contemplated.

d. **Analysis:**
(1) Natural mode shapes and frequencies of the system coupled with the model test bed shall be calculated. These calculations are intended to be used to identify potential resonance or other instabilities, which might be alleviated during the design phase. At the discretion of the RPE/TE or FSH, the critical natural modes and frequencies may be determined experimentally. (See Section 2.10e(4))
(2) Dynamic stability analyses will be required only if specified by the RPE/TE or FSH.
(3) The provisions of Section 2.4 (with the exception of Sections 2.4e(1) and 2.4e(2)) shall apply to all rotating components. All of Section 2.4 applies to the nonrotating components in the model.

e. **Structural Testing:** The RPE/TE or FSH shall establish acceptance criteria based on the following requirements:
(1) **Propeller Blades:** One blade from each manufactured set of propeller blades must be tested to three times the maximum expected centrifugal load and tested (usually in bending and/or torsion) to three times the expected aerodynamic load. Such tests may be done statically or dynamically. For example, a 73 percent overspeed test will simulate three times the expected centrifugal load. At the discretion of the RPE/TE or FSH, such tests can be made on a prototype blade or on a test specimen, which simulates the critically loaded part of the blade (for example, root portion of the blade).
(2) **Rotor Blades:** One blade from each manufactured set of rotor blades shall be tested to 1.25 times the maximum expected centrifugal load. This test may be done statically or dynamically. At the discretion of the RPE/TE or FSH, the test can be made on a test specimen, which simulates the critically loaded part of the blade.
(3) Frequency response checks are to be made for each blade while clamped in a fixture at the root. The frequency checks are to be used to determine that the blades are structurally

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similar by comparing the first mode (usually bending or torsion) frequency and damping characteristics.

(4) Appropriate testing, including a modal survey of the assembled model system, will be conducted to determine or verify critical natural modes and frequencies prior to demonstration testing.

f. **Balancing:** The difference in weight and center-of-gravity between various blades in a given propeller or rotor assembly shall be as small as practical. The assembled propeller or rotor system, excluding rotating controls or instrumentation wiring, shall be either statically or dynamically balanced such that the imbalance force shall not exceed the magnitude of that oscillatory force for which the highest critically stress component of the system will have "infinite" fatigue life.

(1) For static balancing, the imbalance force F is given by the relationship

$$F = \left[\frac{S_u}{g}\right]^2$$

where S_u, is the measured maximum static imbalance about the rotational axis, _ is the maximum design rotational speed, and g is the acceleration due to gravity. (Illustrative units for the terms in the equation are: lbf for F, in.-lbf for S_u, radians per second for _, and in./sec^2 for g.)

(2) For dynamic balancing, the imbalance force shall be the maximum dynamic force measured directly (or derived from measured data) while operating the propeller or rotor over the planned rotational speed range up to the maximum value.

g. **Demonstration Testing:** Demonstration run-up testing of the model system (test configuration) is required prior to tunnel entry. Whether such tests are to be done in a vacuum or test medium (air, heavy gas, and so forth) is to be determined by the RPE/TE and/or the FSH. Such tests shall demonstrate safe operation over all operational speed ranges up to 20 percent overspeed for propeller systems and 10 percent overspeed for rotor systems, unless the RPE/TE and FSH approves a lower speed, because of aeromechanical stability considerations.

h. **Inspection:** All components of the rotating system including blades, drive shaft, bearing, hub, and so forth, shall be thoroughly inspected at time of manufacture and assembly, and at established intervals during usage. Specific inspection requirements shall be established by the TPE/TE/RPE.

2.11 NONDESTRUCTIVE EXAMINATION

All materials used for critically stressed components (excluding fasteners) are to be subjected to 100 percent volumetric nondestructive examination (NDE) for cryogenic model systems. Noncryogenic model systems NDE requirements are to be established by the TPE/TE/RPE.

a. **Metals:** Surface contact or immersion NDE methods may be used for ultrasonic inspection. Liquid penetrant, magnetic particle, or eddy current inspection method may be used for surface inspections. The standards and specifications for ultrasonic inspection of critically stressed components are given in NASA TM 84625, "Fabrication Division Ultrasonic Inspection Specification for Critically Stressed Components." Radiographic and surface inspection standards and specifications are given in Section V of the ANSI/ASME Boiler

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Pressure Vessel Code. As a minimum, surface inspection shall be performed on critically loaded, final machined components in those areas, which have the potential for crack formation.

b. **Composite Material Inspection:** Translucent visual inspection, as defined in the ASME Code Section-V, Articles- 9 & 28, is to be used (where possible) during fabrication to check for delaminations, inclusions, contaminations, fiber orientation, and other defects. All critically loaded composite components shall be examined by both visual and ultrasonic methods for the final inspection. No cracks, delaminations, disbonds or other structurally significant defects are allowed. Other specialized techniques may be acceptable if approved by the FSH/MSE/TPE/TE. Tap testing is a valuable screening/preliminary test but has been superseded by new ultrasonic technology.

c. **Inspection Personnel:** All inspection personnel are to be certified to Level II of the recommended practice of ASNT Publication SNT-TC-1A or its equivalent. Inspectors who perform tap tests should be certified to Level-II in the ultrasonic inspection method.

2.12 ELECTRICAL EQUIPMENT AND COMPONENTS

All electrical devices, wires, and insulation used in model systems must be capable of operating within the test environment and will be consistent with good design practice and safe operating procedures.

2.13 SPECIAL PROVISIONS FOR MODEL SYSTEMS ACCEPTANCE FOR TESTING

a. **Previous Tests:** Models previously tested in the same and/or other facilities may be tested at LaRC with FSH approval. The request for approval will include, as a minimum, documented evidence that:
   (1) The model was tested to loads equal to or higher than anticipated in the proposed test.
   (2) A fatigue evaluation that demonstrates the design life of the model will not be exceeded during the LaRC tests.
   (3) Critically stressed components will undergo an NDE prior to wind tunnel testing.

b. **Static Load Tests:** With FSH approval, static load tests may be conducted in lieu of stress analysis. These static tests are to be based on worst load case(s) and indicate no permanent deformation when carried to either:
   (1) Twice the predicted operating load, where the loads can be directly and continuously monitored during wind tunnel testing. Plots of loads versus deflections for a complete loading cycle will be included in the Model System Report.
   (2) Three times the predicted operating load, where the loads cannot be directly monitored during wind tunnel testing. Examples are slats, ailerons, elevators, rudders, and flaps.

c. **Special Tests:** In situations where actual aircraft and/or components are to be tested, acceptance for testing can be based on wind tunnel loads being equal to or less than design limit loads for flight. In other cases, such as aerodynamic models, it may be necessary to provide additional instrumentation, monitor critical components, install safety catches, and/or perform special proof loading. The FSH must approve the acceptability of models and/or components to be tested and/or used under the provisions of this section.

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2.14 FORCE BALANCE DESIGN AND IN-SERVICE INSPECTIONS

a. **Stress Analysis:** Force balance stresses shall be determined based on well established design practices and will conform to Methods 1, 1A, or 2 as described in Section 2.6.
   (1) For a force balance utilizing Method 1 or 1A, the allowable stresses shall be determined according to the same criteria as described in Section 2.6, paragraph b & c (smaller of one-quarter ($^1/_4$) of the minimum ultimate strength or one-third ($^1/_3$) of the minimum yield strength of the material).
   (2) Since the stress state in the model system structure must be well understood to a high level of confidence, a Method 2 approach is more commonly used for force balances. The allowable stress table given in Section 2.6, paragraph d, may be used to determine the combined stress intensity allowables. As an alternative approach to computing the individual stress components required in section 2.6, the allowable von Mises stress due to combined design loads on force balances utilizing Method 2 shall be established by the smaller of the values of yield stress or $^2/_3$ of the ultimate strength.
   (3) Individual structural components or subsystems can be designed to the allowables of either Methods 1, 1A, or 2 in combination as long as the analysis requirements are met for each method.

b. **Fatigue and Fracture Analysis:** Identify the highest stress points in the balance (for example, in the stress concentrations where crack initiation and growth would most likely occur). Such locations will be documented in the Balance Stress Analysis Report as control points for fatigue and fracture analysis and periodic in-service inspection. Fracture analysis is required only for cryogenic balances. For a particular balance, the balance design review panel will determine the fatigue analysis requirements (which may deviate from Appendix A) and the fracture analysis requirements (which may deviate from Appendix B).

c. **Failure Modes Analysis:** Perform a failure modes analysis to establish single and/or multiple point failures that could result in model loss. This analysis will be documented in the Balance Stress Analysis Report.

d. **Static Tests and Calibrations:** All balances must be statically tested to maximum predicted combined tunnel loads to verify the design, and calibrated for electrical output (including sensitivities, interactions, and repeatability).

e. **Testing Frequency:** As a minimum, each balance will be loaded to its combined load limit as defined in paragraph d within 12 months prior to the tunnel entry unless the balance has less than 1,500 hours of tunnel use since it was last statically load tested. Such tests will be aimed at assuring that all beams (flexures) and critically loaded components are intact and undamaged.

f. **Inspections:** All balances will be thoroughly inspected at time of manufacture, and at the same established intervals detailed in paragraph e. above for the presence of surface and internal cracks and defects, particularly in areas of stress concentrations and the control points as identified in paragraph b. above. Inspection requirements as a minimum include a visual microscopic inspection and a comparison of the unloaded balance electrical outputs. Other specific inspection requirements will be the responsibility of the FME.
   Design Evaluations for Non Accessible Balances: For balances in which the control points specified in paragraph b. above cannot be inspected without complete disassembly or are inaccessible due to the geometry of the balance, a thorough evaluation of the design must be performed for certification of tunnel use. The evaluation must include:

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(1) Fatigue life assessment considering past usage history (where available) based on stresses at the control points.
(2) Identify a containment system that will provide model retention in all failure modes of the balance identified in paragraph c above.
(3) Derating of the balance in the absence of sufficient information to perform paragraph (1) and (2) above.

g. **Maximum Loads:** Balance design loads as established by the FME are not to be exceeded during the wind tunnel test.

h. **Documentation:** Design, analysis, testing, and inspection reports for all balances will be documented or compiled by the FME and made available to the FSH for inclusion in the Model Systems Report.

i. **Reviews:** The balance design will be reviewed as a part of the Model System Informal Engineering Review or Formal Engineering Design Review, as required.

j. **Special Provisions for Balance Acceptance for Testing:** In cases where the Balance Stress Analysis Report is unavailable or incomplete, either of the following sections may be applied with FSH and FME approval.

(1) **Previous Tests:** Balances previously tested in the same and/or other facilities may be tested at LaRC. The request for approval will include documented evidence that each of the three following conditions is satisfied.
(a) The balance was tested to loads equal to or higher than anticipated in the proposed test.
(b) A fatigue evaluation that demonstrates the design life of the balance will not be exceeded during the LaRC test.
(c) Critically stressed components will undergo an NDE prior to wind tunnel testing.

(2) **Static Load Tests:** Static load tests may be conducted in lieu of stress analysis. These static tests are to be based on the maximum predicted combined loads and indicate no permanent deformation when carried to twice the predicted operating load. Plots of applied load versus balance deflection and electrical output for a complete loading cycle will be included in the Balance Stress Analysis Report.

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CHAPTER 3

CERTIFICATION OF STINGS AND OTHER MODEL MOUNTING HARDWARE AND GENERAL PERIODIC IN-SERVICE INSPECTIONS OF MODELS

3.1 INTRODUCTION

All model support hardware including stings, knuckles and other pieces of equipment shall be inspected on a regularly scheduled basis. If a part is critically loaded, an inspection criterion shall be determined during the design stage.

3.2` NEW STING AND MODEL MOUNTING HARDWARE

Maximum load limits based on allowable design stress are to be established for each sting and other model mounting hardware. The sting and associated hardware are to be inspected at the time of manufacture and at least once per year during usage. Stings and associated hardware used infrequently (e.g., time between use is often greater than one year) are not required to be inspected annually, but they shall be inspected prior to use if it has been more than a year since the last inspection. The stings and associated hardware shall be inspected for the presence of surface cracks, signs of wear or defects, particularly in areas of stress concentration. Specific inspection requirements are to be established and documented by the RPE/TE/TPE and/or FSH. Documentation of inspection requirements shall be included in the Model Systems Report.

3.3 EXISTING EQUIPMENT

Maximum load limits based on allowable design stress are to be established for each sting and other model mounting hardware. Existing equipment shall be inspected at regular intervals determined by the FSH with the aid of the MSE. Stings and associated hardware used infrequently (e.g., time between use is often greater than one year) are not required to be inspected annually, but they shall be inspected prior to use if it has been more than a year since the last inspection. The stings and associated hardware shall be inspected for the presence of surface cracks, signs of wear or defects, particularly in areas of stress concentration.

3.4 GENERAL PERIODIC IN-SERVICE INSPECTIONS OF OTHER MODEL HARDWARE

Other model system components such as lifting surfaces, flaps, fasteners, and so forth, may require periodic inspection to guard against fatigue failure. Surfaces and areas that may require inspection shall be identified and inspection requirements specified by the RPE/TE/TPE and/or FSH. Inspection requirements shall be documented and included in the Model Systems Report.

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CHAPTER 4

QUALITY ASSURANCE

4.1 INTRODUCTION

This chapter provides the detail quality assurance criteria for wind-tunnel model systems to be tested at LaRC. These criteria are intended to assure that the as-built model system hardware meets the model system design specifications.

4.2 IMPLEMENTATION RESPONSIBILITY

Specific quality assurance criteria will be determined in view of model system complexity and criticality with regard to model system failure and/or facility damage. Responsibility for determining specific quality assurance requirements and compliance for the different categories of model systems is assigned as follows: As a minimum, components identified as critically loaded/stressed (including fasteners) whose failure can result in critical or catastrophic facility damage/injury, as defined in LPR 1740.4, "Facility System Safety Analysis and Configuration Management," shall meet all requirements of this chapter.

a. **LaRC (In-House):** LaRC TPE, or RPE/TE if a TPE is not assigned.
b. **Contract:** LaRC TPE, or RPE/TE if a TPE is not assigned, will approve quality assurance requirements and/or standards implemented by the contractor.
c. **User-Furnished:** The user will furnish documentation, which gives evidence of compliance with the intent of this Chapter. This documentation will be included in the Model Systems Report (see Chapter 5) that is submitted to the FSH. The criteria given in this Chapter provide the basis for judging the adequacy of user-furnished model systems quality assurance implementation. The RPE/TE is responsible for ensuring that the report meets the requirements of this document.

4.3 QUALITY ASSURANCE CRITERIA

a. **Procurement:**
   (1) **Purchase Orders:** All purchase orders (see LMS-CP-4505, "Prepare Purchase Request And Supporting Documents"), for model systems parts and materials will identify procurement quality assurance and inspection acceptance criteria.
   (2) **Receiving Inspection:** Receiving inspection and acceptance of hardware and all documentation thereof is the responsibility of the TPE/ RPE/TE ordering the hardware. When requested, receiving inspection will be performed and documented by a Quality Assurance Specialist (QAS) on incoming materials, parts, and equipment to assure conformance to drawings and/or procurement documentation.
   (3) **Acceptance/Rejection of Procured Articles:** The documentation of articles and materials will reference the purchase order number, purchase order item number, contract number (if applicable), supplier name, part number, raw material identification information, quantity accepted, and the inspector's stamp or signature. Articles, which do not conform to drawings or specifications and/or do not have adequate or correct data, are to be held for disposition.

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(4) **Supplier Documentation**: Evidence of the following required supplier inspections and tests, as defined in the purchase documentation, are to be verified at receiving inspection:
   (a) Material certification test report.
   (b) Evidence of supplier inspection acceptance.
   (c) Certification of heat treatment process.
   (d) Certification that the end-item is from the material specified.
   (e) Test data.
   (f) Inspection reports.
   (g) Other documentation as specified on the purchase order.
   Upon completion of receiving inspection, all supplier data documentation will be maintained by the QAS and delivered with the hardware.

b. **Fabrication:**
   (1) **Traceability and Control:** Raw materials and parts used in the fabrication and assembly of model systems will be controlled to maintain identification and traceability.
   (2) **Controlled Storage:** Critical raw materials, parts, and fasteners will be stored in a dedicated, controlled access storage area.
   (3) **Configuration Control:** Configuration of the end-item hardware will be maintained by the TPE/RPE/TE through the control of drawing and specification changes. The TPE/RPE/TE is responsible for assuring that obsolete drawings/specifications are withdrawn and destroyed.
      (a) **Identification:** When possible, model system hardware shall be identified by electrolytic etch or other methods that may be appropriate, on a surface location, which will not affect flow or structural integrity. Identification information (such as model number, model system name, drawing number and part number, load capability, use limitation, contractor name, and so forth) and its location, as determined by the TPE/RPE/TE, will be specified on the drawing. The model identification shall be posted on the model's container.
      (b) **Drawing and Specification Control:** Drawings and specifications will define the complete as-built configuration and provide a record of the design. All drawings, specifications, and subsequent revisions shall be reviewed by the TPE/RPE/TE. A copy of all revised drawings shall be provided to the fabrication quality organization for use in the final inspection of the hardware.
      (c) **Red-Line Changes:** Red-line changes may be used to correct or update drawings during the fabrication process when changes are approved by the TPE/RPE/TE. All red-line changes will be initialed and dated on the face of the fabrication drawings prior to implementation.
   (4) **Fabrication/Inspection Plan:** If required, the TPE/RPE/TE is responsible for coordinating the fabrication and inspection effort with the fabrication Lead Technician and the QAS. The manufacturing planning will be documented in a LF 136," "Fabrication and Inspection Operations Sheet (FIOS)," CID 5640, “Requesting, Performing, and Closing Fabrication Services Requests,” or equivalent, preferably by the Lead Technician.
      (a) **Content:** The FIOS defines the premanufacturing inspections, in-process manufacturing steps, special processes and inspections, and post-manufacturing assembly inspections consistent with the requirements set forth by the TPE/RPE/TE.

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(b) **Identification:** The FIOS is to be identified by the model number, model system name and associated drawing numbers.

(c) **Processes/Inspection Checklist:** In formulating the process/inspection checklist to cover the different phases of manufacturing, the following items should be considered:

(1) **Pre-Fabrication:** Receiving inspection, identification, raw material certification (including chemical composition, physical properties, nondestructive examination, and heat treat verification), controlled storage and shop order traveler.

(2) **In-Process Fabrication:** Witness critical processes (for example, heat treat, welding, soldering), dimensional and tape verification.

(3) **Post-Fabrication and Assembly:** Visual inspection for surface imperfections and assembly fits, physical dimensions, and witness final assembly, pressure tube flow, and/or leak tests.

(d) **Review and Approval:** The FIOS shall be reviewed by the QAS and approved by the TPE/RPE/TE.

(e) **Documentation:** The FIOS for fabricated systems shall be maintained with the documentation package and submitted with the hardware.

c. **Nonconforming Hardware Control:** When an article does not conform to applicable drawings, specifications, or other requirements, it will be identified as nonconforming, segregated to the extent practical, and the disposition shall be documented using a LF 143 "Nonconformance Failure Report (NFR)." Documentation on a LF 136,"Fabrication and Inspection Operations Sheet (FIOS)," following CID 5640 or an equivalent form and process maybe used as determined by the TPE/RPE/TE.
NOTE: Material Review Board: Membership usually consists of representatives from engineering, quality assurance, research, and facility safety as applicable. As a minimum, the MRB will include the TPE/RPE/TE and the QAS. LF 143, Part B – Cognizant Engineer signature may be that of his/her designee. Copies of all nonconformance reports are to be provided with the hardware.

d. **Metrology Control:** Instruments used to measure or verify compliance to drawing and specification requirements are to be in current calibration with evidence of calibration displayed.

e. **Handling, Packing, and Shipping:** All hardware will be protected from damage during all phases of manufacturing and shipping. The TPE/RPE/TE will document any special handling, packing, and shipping requirements for model system hardware. Shipping containers are to be designed to assure safe arrival and ready identification. Containers for finished hardware will provide identification for individual parts and will contain a complete set of as-built drawings including assembly procedures.

4.4 RECORDS

Upon completion of fabrication of the model system, the quality assurance records will be incorporated into the Model System Report by the TPE/RPE/TE as required by Chapter 5.

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CHAPTER 5

DOCUMENTATION

5.1 MODEL SYSTEMS REPORT

a. **General:** A Model Systems Report (in English) is required for all model systems to be tested in mandatory facilities at LaRC.

b. **Delivery Schedule:** The Model Systems Report will be submitted by the LaRC TPE and/or RPE/TE to the FSH according to the schedule established by the FSH. In the absence of an established delivery date, the delivery is to take place at least 4 weeks prior to tunnel entry.

c. **Contents:** The Model Systems Report will contain, as a minimum, the following:

(1) As-built drawings of the configuration to be tested, and where applicable, assembly drawings and installation drawings or sketches, electrical schematics, and wiring diagrams.

(2) Design loads:

(a) Model specifications/requirements.

(b) Derived loads (aerodynamic, mechanical, and thermal).

(c) Life requirements.

(3) Stress report:

(a) Summary of factors of safety.

(b) References (general equations, terms, codes, and computer programs).

(c) Assumptions.

(d) Materials data:

(1) Standard properties.

(2) Adjusted properties (temperature, pressure, stress corrosion, or other environmental effects).

(3) Fasteners.

(e) Method of analysis:

(1) Section sketches showing forces and moments at an adequate number of stations. (Free body diagrams)

(2) Shear and moment diagrams.

(3) Stress analysis for worst case load(s).

(f) Structural joint analysis:

(1) Bolted (with torque requirements and secondary means of retention)

(2) Welded

(3) Brazed

(4) Bonded

(g) Pressurized systems analysis (if required).

(h) Hydrostatic test results (if required).

(i) Specialized analysis (if required):

(1) Fatigue and fracture

(2) Thermal

(3) Finite Element

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(4) Stability report (as required):
  (a) Divergence
  (b) Flutter
  (c) Dynamics
  (d) Buckling
(5) Inspection reports:
  (a) Certification of materials.
  (b) Fabrication and Inspection Operations Sheet (if required). LF 136 "Fabrication and Inspection Operations Sheet (FIOS)," CID 5640, or equivalent
  (c) Inspection procedures.
  (d) Nonconformance reports.
  (e) Quality assurance report.
(6) Test reports (if required):
  (a) Material properties.
  (b) Loads tests.
  (c) Modal survey.
  (d) Static and dynamic balancing.
  (e) Demonstration run up.
(7) Deviation requests and supporting documents.
(8) Design review documents, action items, and their disposition.
(9) List of critically loaded/stressed components:
  (a) Include component failure effect on the facility.
  (b) Cross-reference appropriate quality assurance documents (e.g., inspection reports, material certifications, etc.) for components whose failure can result in a critical of catastrophic failure.

d. **Retention:** All Model Systems Reports and drawings shall be sent to Engineering Drawing Files for retention per LPR 7320.1, “Engineering Drawing System.”

5.2 ASSEMBLY, INSTALLATION, AND CONFIGURATION CHANGE PROCEDURES

a. **General:** A model system assembly, installation, and configuration change procedure should be established as early as possible, preferably at a pretest meeting, for all model systems to be tested at LaRC.
b. **Delivery Schedule:** Documentation of the procedures will be submitted to the LaRC RPE/TE no later than 4 weeks prior to the tunnel entry date according to the schedule established by the RPE/TE.
c. **Contents:** Typical procedures and/or drawings will contain sequential assembly steps, torque values, alignment criteria, and so forth, necessary to assemble, install, and check out all hardware in the LaRC facility as well as permit model configuration changes during the test program.

5.3 PERMANENT MARKING OF MODEL COMPONENTS, MODEL ASSEMBLIES AND MODEL BOXES

a. **Model Assembly:** The main model assembly shall be permanently marked with the model number assigned to that model.

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b. **Model Components:** If possible, each model component should be marked with the drawing number assigned to that part.
c. **Model Boxes:** Each model box shall be permanently marked with the model number assigned to that model.

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CHAPTER 6

DEVIATIONS

6.1 GENERAL

When a deviation from the requirements of this guide is considered necessary, a written request for approval is to be submitted to the cognizant FSH. Approval or denial of the request will be documented by the FSH and retained in the facility files.

6.2 DEVIATION REQUESTS

The deviation request will be submitted through the TPE/RPE/TE to the cognizant FSH. The FSH will be responsible for providing or obtaining the evaluation of the rationale for the deviation. In performing this evaluation, the FSH may request assistance from the FME, MSE, LaRC organizational elements, or other committees, as required, to verify the adequacy of technical assessments and acceptability of additional risks. An information copy of all deviation requests and their disposition is to be submitted to the Office Head, Office of Mission Assurance, Office of Safety & Facility Assurance.

The deviation request will contain, as a minimum, the following information:

(a) Identification of the article or system under consideration.
(b) The requirement for which the deviation is being processed.
(c) The reason for which the requirement cannot be fulfilled.
(d) The technical assessment that the deviation from a requirement is acceptable.

6.3 APPROVAL AUTHORITY

In instances where a model system failure can be expected to result in only minor damage to the facility, the FSH is authorized to approve deviation requests. For failure situations that could be expected to cause significant facility damage, the LaRC Competency Director of the involved facility must approve all deviations. In any instance where major facility damage might be expected in the event of a model system failure, concurrence must be through the research Associate Director.

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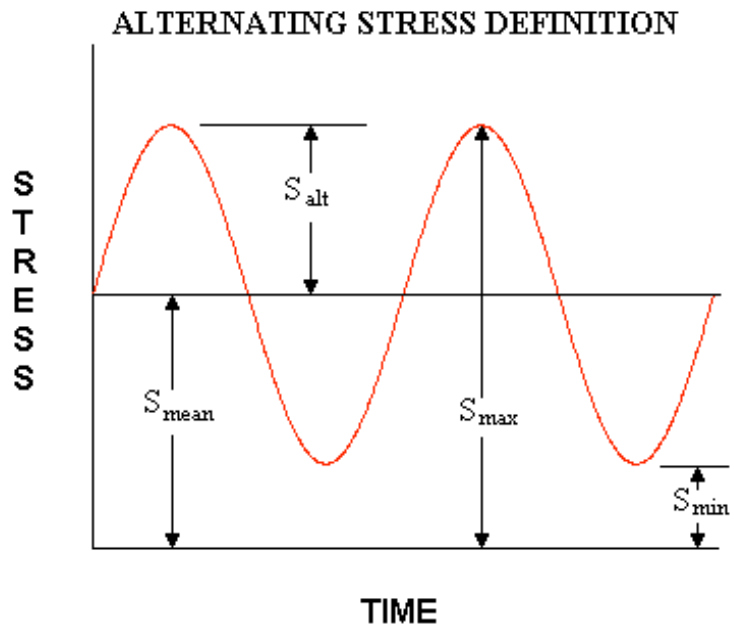
APPENDIX A

FATIGUE DESIGN

A.1 ALTERNATING STRESS DEFINED

Given the following illustration of a fluctuating stress around a mean value:



The definitions needed to perform a fatigue analysis are as follows:

S_{min} = minimum stress

S_{max} = maximum stress

S_{mean} = mean stress = $(S_{max} + S_{min})/2$

S_{alt} = alternating stress = $(S_{max} – S_{min})/2$

Stress Ratio = R = S_{min}/S_{max}

In the above example, the ordinate value of stress is the maximum stress. Fatigue curves (S-N data) are normally developed for full stress reversal, that is, R = -1 such that $S_{alt} = S_{max}$ (or $S_{mean} = 0$) for this case.

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A.2 FATIGUE CURVE

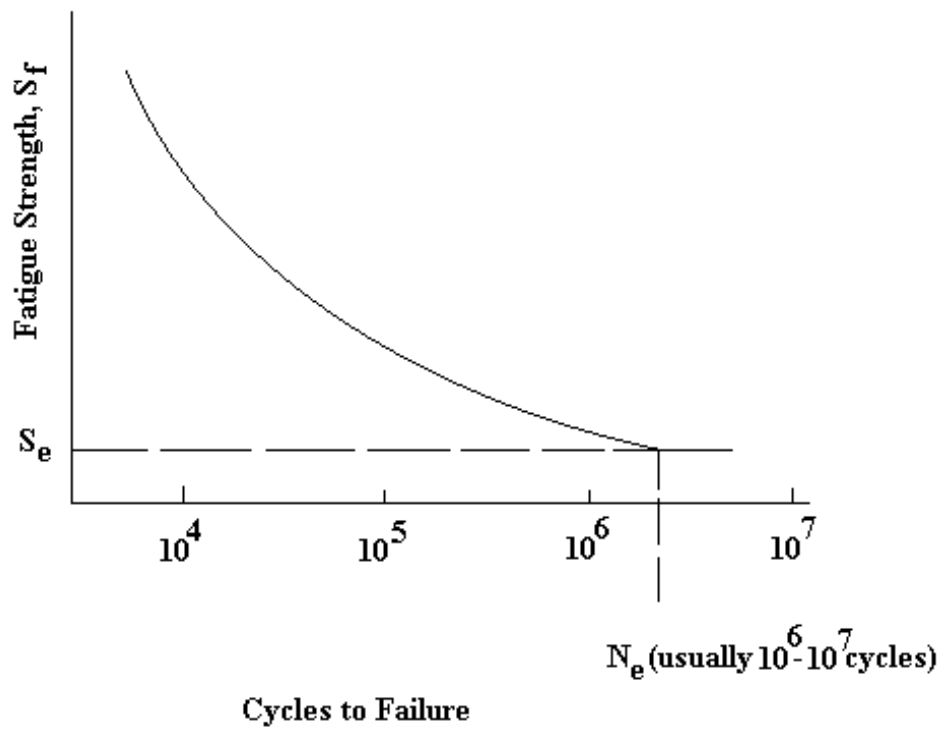
When available, fatigue (S-N) data for the material at test temperature shall be used. However, when S-N data are not available, a general rule of thumb for the average endurance limit S_e, (stress which can be applied an infinite number of times without failure) for different materials at room temperature is for most product forms and heat treatments as follows:

(Mean endurance limit of the rotating beam specimens)

Steel Alloys	Aluminum and composites
S_e □ 0.5 S_u where S_u □ 200 Ksi	S_e □ 0.3 S_u
S_e □ 100 Ksi where S_u > 200 Ks	

As a rule, a design, which is within the allowables of Method 1 (Section 2.6b) will usually, provide a safe-life (usually infinite) design. However, this should not preclude the designer from calculating the fatigue life of the system.

An example of a typical S – N curve is as follows:



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A.3 APPLICATION

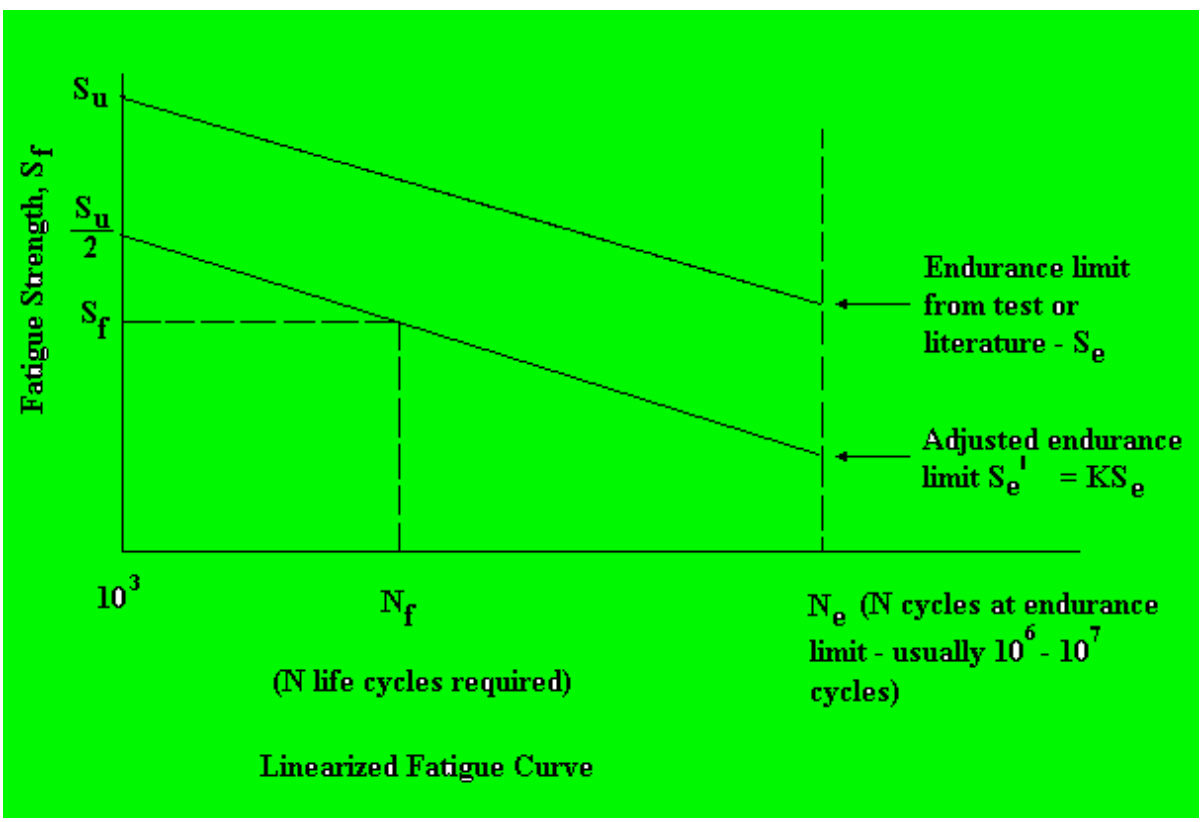
a. **Fatigue Strength Modifying Factors**: In computing the fatigue life, fatigue endurance limit modifying (reduction) factors shall be applied to the appropriate fatigue curve. Modifying factors to be considered are;

(1) Surface Finish Factor
(2) Scale Factor
(3) Reliability Factor (for example, R = 0.00000, K_r = 0.659)
(4) Temperature Factor
(5) Other miscellaneous factors as required:

NOTE: A fatigue strength modifying factor of K = 0.5 may be used to cover items (1) through (5).

b. **Linearized Fatigue Design Curve**: If desired, the fatigue (S – N) curve may be linearized for design applications to more conservatively allow for application of fatigue strength modifying factors, and to account for the effects of mean stress. Stress concentration factors shall be applied when computing the maximum combined stress. The modifying factors are used to reduce the endurance limit as illustrated in the following example of a linearized fatigue curve:

c. **Effects of Mean Stress**: Next, to account for the effect of mean stress (S_{mean}), a modified



Goodman diagram shall be constructed to determine the allowable alternating stress, S_a, as illustrated in the following figure:

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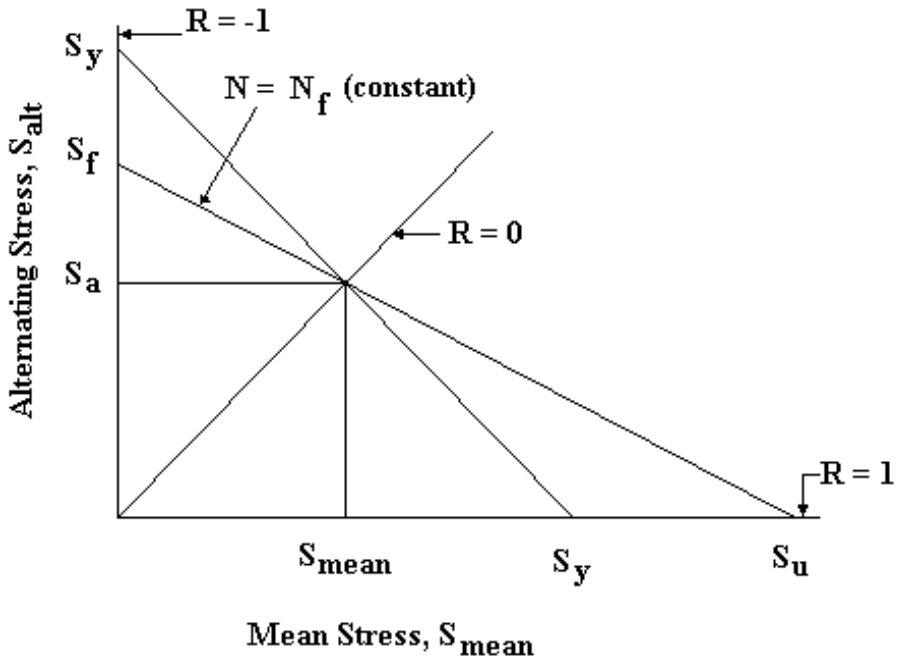

The allowable alternating stress, (S_a) allow, can be determined from the diagram; or by linearizing the S – N diagram and the Goodman diagram, the following equations may be used to calculated S_a for K = 0.5 given a mean stress, S_{mean}, and a required number of cycles, N_f.

Case 1

For $$S_{mean} < \frac{S_y - S_f}{\left[1 - \frac{S_f}{S_u}\right]} : (S_a)\text{allow} = S_f \left[1 - \frac{S_{mean}}{S_u}\right]$$

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Case 2

For $$S_{mean} > \frac{S_y - S_f}{(1 - \frac{S_f}{S_u})} : (S_a)allow = S_y - S_{mean}$$

where

$$S_f = \frac{S_e'}{2} \left[\frac{N_f}{N_e} \right]^b$$

and

$$b = \frac{\log(S_e') - \log(S_u)}{\log(N_e) - \log(1000)} = \frac{\log\left[\frac{S_e'}{S_u}\right]}{\log\left[\frac{N_e}{1000}\right]}$$

Note: For applicability of fatigue analysis requirements to wind tunnel balances, reference Section 2.14 paragraph "b".

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APPENDIX B

FRACTURE MECHANICS ANALYSIS

B.1 FATIGUE CRACK GROWTH ASSESSMENT

a. General: In cases where fatigue cracking causes failure, it is appropriate to use fracture mechanics analyses, also called damage-tolerance (DT) analyses, to predict fatigue lives of metallic structures. The DT methodology assumes all structural material is damaged and contains cracks or crack-like flaws that can propagate to failure under cyclic loading. DT life predictions are made in terms of fatigue loading, an initial crack size, fracture toughness, and fatigue crack growth behavior (da/dN versus _K) for the material of concern. Fatigue life is calculated as the number of load cycles required for a crack to propagate from some initial size to the critical size where failure occurs. When no cracks are detected during NDE inspections, the largest crack that can be missed by a crack inspection must be assumed present to ensure conservative predictions. A conservative fatigue life prediction is then used to establish regular inspection intervals. Multiple inspections are planned during the fatigue life so missing a fatigue crack during a single inspection does not cause catastrophic failure. DT is the most conservative fatigue life management method, but inspection for cracks, especially small ones, is an expensive and time consuming process. These extra efforts are warranted for scenarios where failure must be avoided (*e.g*. critically stressed parts where failure may cause injury or destroy expensive equipment). Less rigorous life management methods (see Appendix A) may be the best life management method for non-critical or inexpensive parts where periodic part replacement is a cost-effective option.
The fatigue life criteria prescribed in this appendix provide three levels of analysis that allow the designer to meet the fracture criteria required in this document. Level one defines two ways to establish the fracture toughness with all applied stresses causing damage. Level two employs a fatigue-crack-growth threshold which defines a stress intensity level where cracks do not propagate thus prescribing a less conservative approach for calculating fatigue life. Level three allows the designer the option of using a commercially available fatigue-crack-growth computer code.

Note: For applicability of fracture analysis requirements to wind tunnel balances, reference Section 2.14 paragraph "b".

b. Required Data: In order to perform a fracture mechanics analysis, it is necessary to have fatigue crack growth and fracture data set at operating conditions, and knowledge of the component stresses and NDE inspection method. The required data, and the preferred order of the source from which to obtain the data is as follows (data source letter a is the optimum source for the data):

(1) _K_{Ic} fracture toughness data
- (a) Test data generated from the specific material by the manufacturer, per ASTM E399, at operating temperature.
- (b) Test data found in literature that matches the heat treat, material chemistry and operating temperature with the integrity requirements of Section 2.3e.
- (c) For Steel Alloys Only, Charpy V-Notch data may be used per Appendix B.1.

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(d) If (a)-(c) are not feasible, the manufacturer must generate fracture toughness data per ASTM E399 at the operating temperature.

(2) Crack growth rate versus the stress intensity factor range (da/dN vs ΔK)

(a) Test data generated for the specific material, per ASTM E647, at operating temperature. Fatigue crack growth data for two steels, at 70°F and –275°F are shown in Figure B.1.

(b) Test data found in literature that matches the heat treat, material chemistry and operating temperature with the integrity requirements of Section 2.3e.

(c) If (a)-(c) are not feasible, the manufacturer must generate fatigue crack growth data (da/dN vs. ΔK) per ASTM E647 at the operating temperature.

(d) If the fracture analysis method given in Section B.1c is used, no fatigue crack growth data is needed.

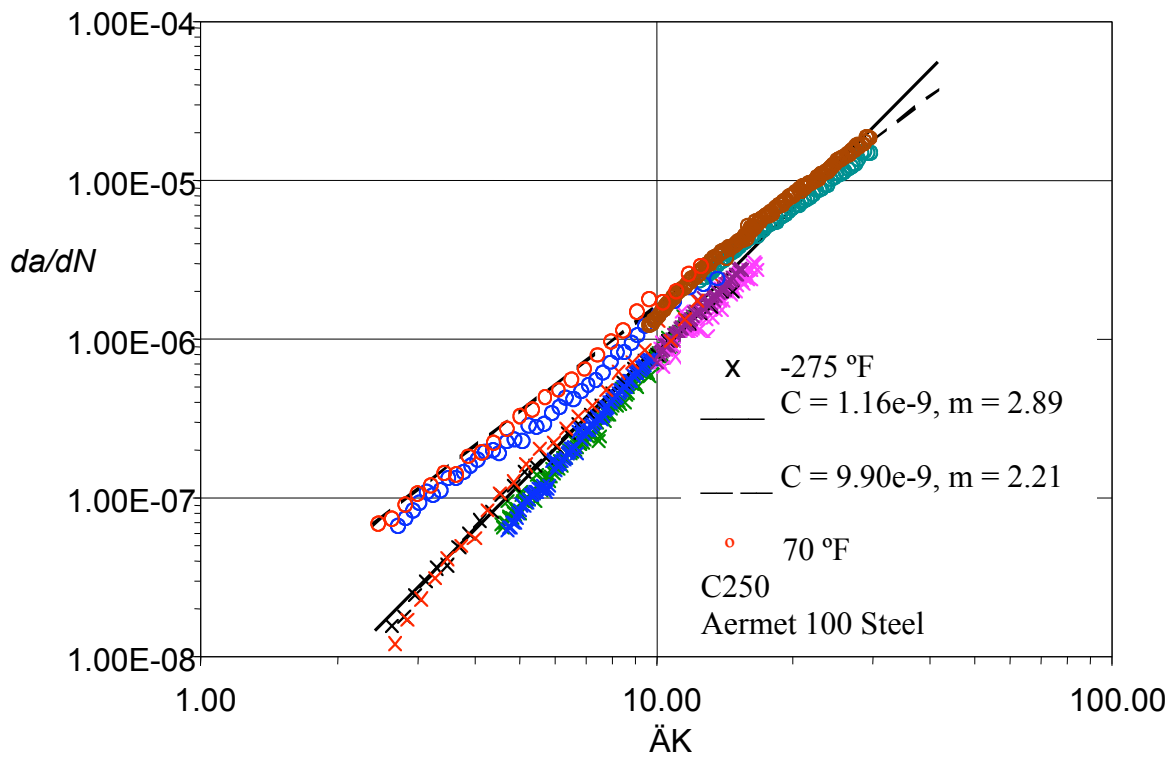

Figure B.1: Fatigue crack growth data (da/dN vs. _K)and curve fits for two steels at 70ºF and –275ºF.

(3) S_{max}, S_{min} maximum and minimum applied stress per cycle

The stress levels are defined in Section 2.6 and are schematically illustrated in Figure B.2.

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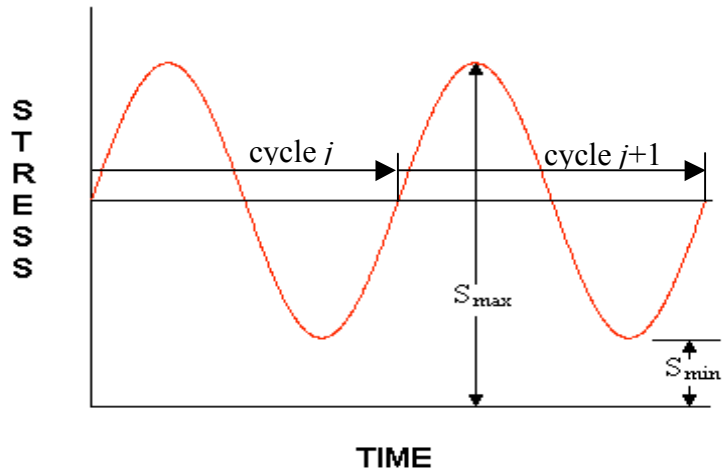

Figure B.2 – Schematic of cyclic stresses.

(4) a_i initial crack size defined by nondestructive inspection (Section 2.11 and Table B.1)

Table B.1 Typical Initial Crack Sizes for Fracture Analysis Based on NDI Methods
(*ref*: Fracture Control Requirements for Space Station, SSP 30558, Rev. B)

NDI Method	Initial Crack Size, a_i (inches)
Eddy Current	0.050
Dye Penetrant	0.100
Magnetic Particle	0.125
Radiographic	0.075
Ultrasonic	0.030

Note: Other allowable initial flaw sizes may be determined using the methods outlined in Section 2.11

c. Fracture Analysis Method: To assess the life of a component, fatigue crack growth data (da/dN, vs. _K), fracture toughness data (K_{Ic}), and knowledge of the nondestructive inspection methods (NDI) are usually required. However, the fracture analysis method outlined in this section does not require crack-growth-rate data. First, an initial crack size, a_i, is defined as the detectable NDI crack size shown in Table B.1 based on the inspection method. To compute the life of the component from this crack, a relation between crack growth rate, da/dN, and the stress intensity factor range, _K, is used such that

$$\frac{da}{dn} = CU^m(\Delta K)^m \qquad (1)$$

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where

$$U = \begin{cases} \left(0.7 - 1.1R^2 + 0.4R^3\right)/\left(1 - R\right) & R \geq 0 \\ 0.7 & R < 0 \end{cases} \tag{2}$$

and, $$R = \frac{S_{min}}{S_{max}} \tag{2a}$$

S_{max} and S_{min} define the maximum stress and minimum stress in the load cycle (see Figure B.2), and C and m are considered to be material constants. Experimental data are used to determine C and m such that a straight line fits the data on a log-log scale as shown in Figure B.1. Extensive data for the material constants C and m for a variety of metals can be found in the technical literature, such as those listed in Section 2.3f. As an alternative, the analyst may use the following relation where E is the elastic modulus.

$$\frac{da}{dN} = 537.0\left(\frac{U}{E}\right)^{2.43}\left(\Delta K\right)^{2.43} \tag{3}$$

The stress intensity range is defined as

$$\Delta K = K_{max} - K_{min} = \left(S_{max} - S_{min}\right)\sqrt{\pi a} \tag{4}$$

where a is the crack length. Assuming the component fails when K_{max} exceeds the plane-strain fracture toughness, K_{Ic}, a critical crack size (*i.e.* the crack size where fracture occurs) can be computed as,

$$K_{Ic} = S_{max}\sqrt{\pi a_c} \qquad \text{or} \qquad a_c = \frac{1}{\pi}\left(\frac{K_{Ic}}{S_{max}}\right)^2 \tag{5}$$

The computation of the total fatigue life can be accomplished by solving equation (1) for crack length after each load cycle and summing these values until the crack length exceeds a_c. Since the crack size, a_1, is known prior to each load cycle, the amount of crack growth, da, caused by one load cycle ($dN = 1$) can be determined by

$$\int_{a_1}^{a_2} da = \int_{N_1}^{N_2} CU^m(\Delta K)^m dN \tag{6}$$

Substituting equation (3) into equation (6), and solving for da yields

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$$da = a_2 - a_1 = C\left(U\left(S_{max} - S_{min}\right)\sqrt{\pi a_1}\right)^n \tag{7}$$

Solving equation (7) for each load cycle and summing the crack extension from each cycle to determine the total fatigue life, N_{tot}, is established when the crack length exceeds a_c such that

$$a = a_i + \sum_{j=1}^{N} da_j = a_i + \sum_{j=1}^{N} C\left(U_j\left(S_{j_{max}} - S_{j_{min}}\right)\sqrt{\pi a_j}\right)^n \tag{8}$$

To complete the fracture analysis, an inspection interval must be established. In the fracture analysis prescribed herein, there must be at least seven nondestructive inspections for cracking during the operational life of the component. Therefore, the total life is divided by eight, and the inspection interval is defined as

$$\text{Inspection interval} = \frac{N_{tot}}{8} \tag{9}$$

such that seven inspections can be made before the safe operating life limit is reached.

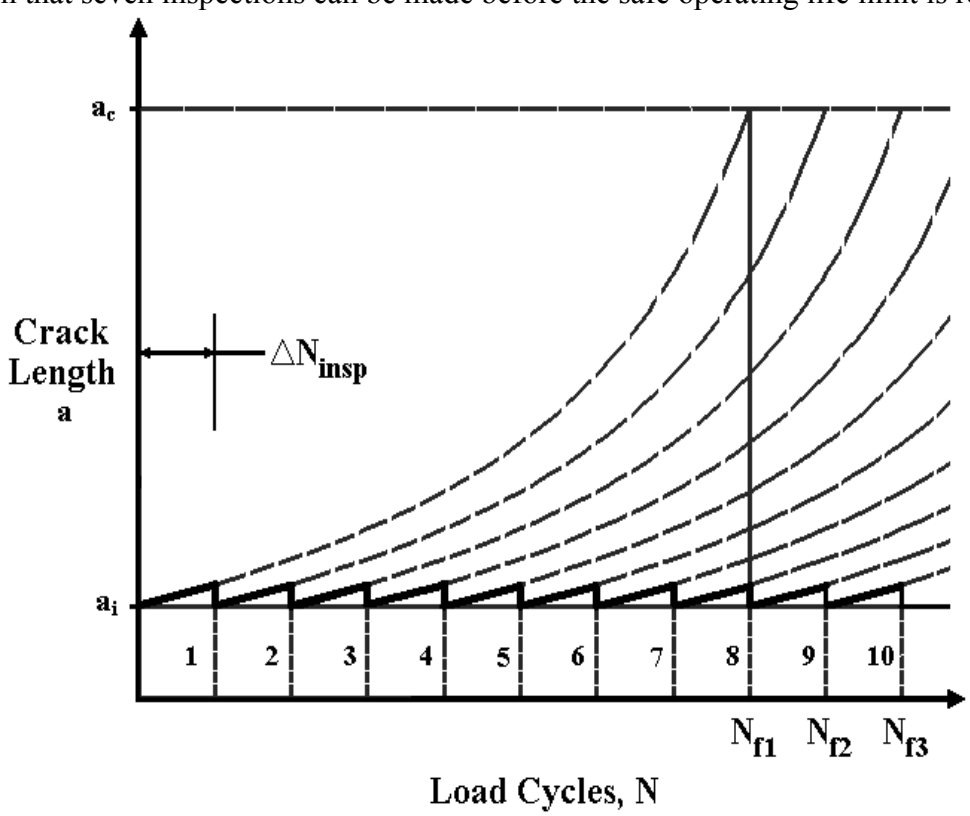

Figure B.3. Schematic illustrating damage-tolerance fatigue-life management.

d. Three Level Fracture Analysis: Use the fatigue crack growth methodology outlined in the previous section. The fatigue life requirement is met by two criteria:
(1) The critical crack size must be at least four times the NDI initial crack size

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$$a_c \geq 4a_1 \tag{10}$$

(2) The total fatigue life, divided by a factor of safety of two, must give enough operating time to perform all required experiments and allow reasonable operating time between nondestructive inspections, *i.e.*:

$$\text{Inspection interval} = \frac{N_{tot}}{8} \tag{11}$$

If no damage is found in the component during an inspection, the load history is erased and the part is assumed to be new. Figure B.3 depicts this concept.

Level 1a: Use the fatigue crack growth methodology outlined in the previous section where the fracture toughness, K_{Ic}, is defined by one of the four data sources described in Section B.1b under K_{Ic} fracture toughness data. If the critical crack size requirement or the factor of safety on total fatigue life outlined above cannot be met, a less conservative approach may be utilized as described next as a Level 1b analysis.

Level 1b: The fracture toughness value, K_{Ic}, may be raised to adjust for part-through thickness effects, termed K_{Ie}, if supported by experimental data. However, the value of K_{Ie} must not exceed 1.2 times K_{Ic}, where K_{Ie} is defined as

$$K_{Ie} = K_{Ic}\left[1 + \frac{K_{Ic}}{S_y}\right] \text{ and } K_{Ie} \leq 1.2K_{Ic} \tag{12}$$

and S_y is the yield stress. Replacing K_{Ic} with K_{Ie} in equation (5) of the fatigue crack growth methodology outlined in the previous section will provide a longer critical crack size and total fatigue life. Using K_{Ie}, the critical crack size requirement or the factor of safety on total fatigue life outlined above must be met.

Level 2: If the critical crack size requirement or the factor of safety on total fatigue life outlined in either of the Level 1 analysis cannot be met, a still less conservative approach may be utilized. The part-through fracture toughness, K_{Ie}, defined in Level 1b may be used in combination with a fatigue crack growth threshold. The threshold, $_K_{th}$, defines a combination of stress level and crack length where cracks do not propagate, *i.e.* any loading below $_K_{th}$ produces no damage. For a variety of steel, aluminum, and titanium alloys, a conservative estimate of threshold is defined as

$$\Delta K_{th} = 0.0001UE \tag{13}$$

where *U* is defined in equation (2) and *E* is the elastic modulus. To utilize the threshold, evaluate equation (10) such that

$$\text{if} \quad U\left(S_{j_{max}} - S_{j_{min}}\right)\sqrt{\pi a_j} \leq \Delta K_{th} \text{ then } da_j = 0 \tag{14}$$

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Level 3: If the critical crack size requirement or the factor of safety on total fatigue life outlined in level 1 or 2 cannot be met, the user is given the option of using a commercially available fatigue crack growth computer code to assess the fatigue crack growth life. The operator of this code is restricted to the following:

(1) The material data used (da/dN vs. _K, K_{Ic}, K_{Ie} and _K_{th}) must meet the integrity requirements outlined in B.1b.
(2) The geometry must be representative of the component under investigation.
(3) The initial NDI crack size may be a function of geometry other than a through crack, as defined in Method 1. The size of the initial flaw is still defined via Table B.1, and the shape of the crack is to be an aspect ratio (*a/c*) of 1.

The fatigue crack growth analysis must be rigorously documented with reference material on the stress intensity factor solution, loading information and material data used. The critical crack size requirement and factor of safety on total fatigue life defined in equations (10) and (11) must be met. If the analysis cannot meet these requirements a reassessment of the loads, component geometry and/or material may be required.

B.2 EXAMPLE OF LIFE CALCULATION

Assume a part for cryogenic operation (–275° F) is being designed for operation in a NASA Langley wind tunnel. A material is selected and a stress analysis has been completed. To perform the fracture analysis, engineer obtains the plane-strain fracture toughness (K_{Ic}) and fatigue crack growth relation (da/dN vs. ΔK) for the material at the operating temperature (outlined in Section B.1b). The properties of this alloy at –275°F are expressed as:

$$C = 1.16\text{x}10^{-9}, \qquad m = 2.89, \qquad K_{Ic} = 65 \text{ ksi in}^{1/2}$$

The operating stresses in the critical region have been determined for each run in the tunnel generating 100 load cycles per run. The part needs to last for 50 runs. In this example S_{max} = 60 ksi, S_{min} = 10 ksi, and the design life is N_{life} = 5,000 cycles.
Dye penetrant has been chosen for nondestructive inspection after every 10 runs which gives an initial crack size of a_i = 0.100 in. and an inspection interval of N_{insp} = 500 cycles.
Based on this information, the critical crack size, at which failure occurs, can be expressed in terms of the fracture toughness and maximum applied stress, as shown in Equation (5) such that

$$a_c = \frac{1}{\pi}\left(\frac{K_{Ic}}{S_{max}}\right)^2 = \frac{1}{3.14}\left(\frac{65}{60}\right)^2 = 0.374 \text{ in.}$$

The total fatigue life of the part can be computed using equation (8) where

$$a = a_1 + \sum_{j=1}^{N} da_j = a_j + \sum_{j=1}^{N} C\left(U_j\left(S_{j_{max}} - S_{j_{min}}\right)\sqrt{\pi a_j}\right)^n$$

$$U = \begin{cases} \left(0.7 - 1.1R^2 + 0.4R^3\right)/\left(1 - R\right) & R \geq 0 \\ 0.7 & R < 0 \end{cases}$$

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$$U = \left[0.7 - 1.1\left(\frac{10}{60}\right)^2 + 0.4\left(\frac{10}{60}\right)^3\right] / \left[1 - \left(\frac{10}{60}\right)\right] = 0.806$$

$$0.374 = 0.100 + N\sum_{j=1} da_j = 0.100 + \sum_{j=1}^{N} 1.16x10^{-9}\left(0.806(60-10)\sqrt{\pi a_j}\right)^{3.89}$$

For the first cycle, j=1

$$da_1 = 1.16x10^{-9}\left(0.806(60-10)\sqrt{\pi 0.100}\right)^{3.89} = 1.20x10^{-5}\,\text{in}$$

For the second cycle, j=2

$$da_2 = 1.16x10^{-9}\left(0.806(60-10)\sqrt{\pi 0.100}\right)^{3.89} = 1.20x10^{-5}\,\text{in}$$

For the third cycle, j=3

$$da_3 = 1.16x10^{-9}\left(0.806(60-10)\sqrt{\pi 0.100}\right)^{3.89} = 1.20x10^{-5}\,\text{in}$$

Hence, after three cycles, the crack length is 0.100036 inches. Continuing this summation, the part will fail at approximately 29,000 cycles.

To meet the Level 1 requirements, the critical crack size must be at least four times the NDI crack size and the inspection intervals and total life, with a safety factor of two, must be manageable.

$$\text{Inspection interval} = \frac{N_{tot}}{8} = \frac{29{,}000}{8} = 3{,}625 \text{ cycles}$$

- The safe predicted life of 14,500 exceeds the design life of 5,000 cycles.
- The predicted inspection interval 3,625 exceeds the desired inspection of 500 cycles
- The critical crack size of 0.374 inches is less than 4 times the NDI crack size of 0.100 inches.

The design fails the critical crack size requirement as prescribed in Section B.1d.

Going to a less conservative approach by adopting a higher fracture toughness is allowable under a level 1b analysis. Using the part-through fracture toughness defined in equation (12), the K_{Ie} is defined as

$$K_{Ie} = K_{Ic}\left[1 + \frac{K_{Ic}}{S_y}\right] = 65\left[1 + \frac{65}{250}\right] = 81.9\text{ksi}\sqrt{\text{in}} \geq 1.2K_{Ic}$$

Therefore, K_{Ie} = 78.0 ksi-in^{-}.

Substituting this value for K_{Ic} in the above example, the new life prediction and critical crack size are

N_{tot} = 46,158 cycles and a_c = 0.538 in.

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To meet the two criteria for fatigue life in Section B.1d, the critical crack size must be at least four times the NDI crack size and the inspection intervals and total life, with a safety factor of two, must be manageable.

$$\text{Inspection interval} = \frac{N_{tot}}{8} = \frac{46{,}158}{8} = 5{,}769 \text{ cycles}$$

$$\text{Total Life} = \frac{N_{tot}}{2} = \frac{46{,}158}{2} = 23{,}079$$

- The safe predicted life of 23,079 exceeds the design life of 5,000 cycles.
- The predicted inspection interval 5,769 exceeds the desired inspection of 500 cycles
- The critical crack size of 0.538 inches is more than 4 times the NDI crack size of 0.100 inches.

This design analysis meets the two criteria requirements for fatigue life.

B.3 CHARPY V-NOTCH RELATION FOR STEEL ALLOYS

In cases where K_{1c} data is not available, an empirical relation exists which relates plane strain fracture toughness to Charpy impact energy (see Barson, J. M.; and Rolfe, S. T.: Correlation Between K_{1c} and Charpy V-Notch Test Results in the Transition Temperature Range: Impact testing of metals, ASTM, STP 466, 1970: pp.281-302). The cited reference proposes the following relationship for steels in the transition-temperature region:

$$K_{Ic} = \left(2E\left(C_{VN}\right)^{3/2}\right)^{1/2}$$

where E is the Young's Modulus, (lb/in^2) and C_{VN} is the impact energy, (ft-lb).
The Charpy V-Notch for Steel Alloys will govern welds, heat affected zones, and base materials. If the manufacturer does not have Charpy data available, published test data available in the literature may be used if the heat treat, material chemistry and test temperature are similar to the operating condition. This literature data must include two independent sources of data and be from a reputable resource such as those defined in Section 2.3f.

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