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Langley Research Center

WIND TUNNEL MODEL SYSTEMS CRITERIA

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PREFACE

P.1 PURPOSE

a. This procedure sets forth criteria for the design, analysis, quality assurance, and documentation of wind tunnel model systems to be tested at Langley Research Center (LaRC).

b. The criteria contained in this directive are intended to prevent model system failure and/or facility damage.

c. 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 in Langley Procedural Directive (LAPD) 1150.2, “Councils, Boards, Panels, Committees, Teams, and Groups.”

d. The purpose of these requirements is to allow wind tunnel model systems with sufficient fidelity to be tested in wind tunnel environments at LaRC. As a result, the design requirements are not as conservative as building standards and therefore, shall not be used for the design of anything other than wind tunnel model systems and their supporting systems (e.g., balances, stings). Design standards for facilities and facility systems are available in the Center Operations Directorate’s LaRC Engineering Standards (https://sites-n.larc.nasa.gov/standards/cod/).

P.2 APPLICABILITY

a. The procedural requirements contained in this document shall apply to all personnel at LaRC, including civil servants, on-site contractors, research associates, outside producers of model systems, students, visitors, and others.

b. In this directive, all mandatory actions (i.e., requirements) are denoted by statements containing the term "shall." The terms "may" or "can" denote discretionary privilege or permission, "should" denotes a good practice and is recommended, but not required, "will" denotes expected outcome, and "are/is" denotes descriptive material.

c. In this directive, all document citations are assumed to be the latest version unless otherwise noted.

P.3. AUTHORITY

a. NPR 8715.3, NASA General Safety Program Requirements.

P.4 APPLICABLE DOCUMENTS AND FORMS

a. NPD 8710.5, Policy for Pressure Vessels and Pressurized Systems.

b. LAPD 1150.2, Councils, Boards, Panels, Committees, Teams, and Groups.

c. LAPD 4520.1, Langley Research Center Requirements for Safety-Critical Products.

d. LAPD 5330.3, Langley Research Center (LaRC) Standards for the Acquisition and Use of Threaded Fasteners.

e. LPR 1710.40, Langley Research Center Pressure Systems Handbook.

f. LPR 1740.4, Facility System Safety Analysis.

g. LPR 7320.1, Engineering Drawing System.

h. LMS-CP-4505, Purchase Requisition (PR) Initiation/Modification/Cancellation and Supporting Documentation.

i. LMS-CP-5640, Requesting, Performing, and Closing Fabrication Services Requests.

j. Langley Center Operations Directorate, LaRC Engineering Standards (https://sites-n.larc.nasa.gov/standards/cod/).

k. NASA-STD-8719.17, NASA Requirements for Ground-Based Pressure Vessels and Pressurized Systems (PVS).

l. NASA-TM-84625, Fabrication Division Ultrasonic Inspection Specification for Critically Stressed Components.

m. NASA-TM-85805, Fastener Load Tests and Retention Systems Tests for Cryogenic Wind-Tunnel Models.

n. NASA-TM-85816, Grain-Refining Heat Treatments to Improve Cryogenic Toughness of High-Strength Steels.

o. NASA SSP 30558, Fracture Control Requirements for Space Station.

p. NASA Contractor Report (CR) 172620, Materials and Techniques for Model Construction.

q. LF 136, Fabrication Inspection and Operations Sheet.

r. LF 143, Nonconformance Report (NCR).

s. AIAA-2001-0757, Cryogenic Model Materials.

t. ASME B31.3, Process Piping.

u. ASME, Boiler and Pressure Vessel Code.

v. ASNT, Recommended Practice No. SNT-TC-1A, Personnel Qualification and Certification in Nondestructive Testing.

w. ASTM E399, Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness Klc of Metallic Materials.

x. Erik Oberg, Franklin Jones, Holbrook Horton, Henry Ryffel, Christopher McCauley, *Machinery's Handbook* (South Norwalk, CT: Industrial Press, Inc).

y. MIL-HDBK-17, Composite Materials Handbook.

z. National Electric Code (NEC).

P.5 MEASUREMENT/VERIFICATION

None

P.6 CANCELLATION

LPR 1710.15 J, dated May 26, 2015, is superseded and shall be destroyed.

David F. Young February 21, 2020
Deputy Director Date

Distribution:
Approved for public release via the Langley Management System; distribution is unlimited.

CHAPTER 1: APPLICABILITY AND IMPLEMENTATION

1.1 INTRODUCTION

1.1.1 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).

1.1.2 The guide also applies to models under the control of LaRC that will be tested at the Wallops Flight Center and at the NASA Armstrong Flight Research Center (these facilities may require criteria in addition to this document).

1.1.3 The criteria are intended to prevent model system loss and/or potential facility damage.

1.1.4 The purpose of these requirements is to allow wind tunnel model systems with sufficient fidelity to be tested in wind tunnel environments at LaRC. As a result, the design requirements are not as conservative as building standards and therefore, shall not be used for the design of anything other than wind tunnel model systems and their supporting systems (e.g., balances, stings). Design standards for facilities and facility systems are available in the Center Operations Directorate's LaRC Engineering Standards (https://sites-n.larc.nasa.gov/standards/cod/).

1.2 APPLICABILITY

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

a. Transonic Dynamics Tunnel

b. 14- by 22-Foot Subsonic Tunnel

c. National Transonic Facility

d. 0.3-Meter Transonic Cryogenic Tunnel

e. 20-Inch Supersonic Wind Tunnel

f. Unitary Wind Tunnel

g. 8-Foot High-Temperature Tunnel

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

1.2.3 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 LAPD 1150.2, "Councils, Boards, Panels, Committees, Teams, and Groups").

1.3 IMPLEMENTATION

1.3.1 The Facility Safety Head (FSH) has the responsibility and authority to implement the requirements in this LPR.

1.3.2 For all in-house and user furnished model systems being tested in a mandatory facility as described in Section 1.2 of this LPR, the FSH shall be assisted by a Model

Systems Engineer (MSE). For other matters, the FSH may elect to be assisted by an MSE. The Technical Project Engineer (TPE), Research Project Engineer (RPE), or the facility's Test Engineer (TE) has the responsibility of ensuring that the model system design meets the criteria of this guide.

1.3.3 Any deviations to these criteria shall be addressed according to the deviation procedure given in Chapter 6.

1.3.4 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.

1.3.5 The FSH shall determine the need for this review.

1.4 REVIEWS

1.4.1 Model system reviews shall be conducted to help ensure that the systems are functional, meet the research requirements, and meet the criteria set forth in this guide.

1.4.2 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.

1.4.3 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.

1.5 ADDITIONAL REQUIREMENTS

1.5.1 Requirements beyond those specified in this guide shall be imposed as may be required.

1.5.2 The FSH is authorized to implement additional requirements as necessary.

1.6 WIND TUNNEL MODEL SYSTEMS COMMITTEE

1.6.1 The Wind Tunnel Model Systems Committee, as outlined in LAPD 1150.2 has ownership of this document.

1.6.2 All requests for additions, deletions, and changes shall be forwarded to the Chairman of this committee.

CHAPTER 2: DESIGN AND ANALYSIS

2.1 GENERAL

2.1.1 **Design Loads:** The design loads data shall be established by research personnel and consistent with safe operating limits of the facility.

2.1.1.1 The design loads data shall be a part of the Model Systems Report (see Chapter 5).

2.1.1.2 Documentation**:** The documentation shall include, where applicable, aerodynamic and thermal loads for the extremes of the test conditions seen for the various model configurations, design cycle life requirements, and inertia driving forces and frequencies for dynamic and transient testing.

2.1.1.3 **Critically Loaded/Stressed Components**: A list of all critically loaded/stressed components, including fasteners, shall be generated and included in the Model Systems Report.

2.1.1.3.1 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.

2.1.1.3.2 When identifying impact on the facility, the secondary effects of the failure shall 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

2.2.1 Unless otherwise specified, applicable provisions of the following standards, codes, requirements, or handbooks listed here, and those by the included institutions, 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, Langley Research Center Pressure Systems Handbook

k. National Institute of Standards and Technology (NIST)

l. Aerospace Structural Metals Handbook—Department of Defense (DOD)

m. Advanced Composite Design Guide—DOD/NASA

n. Metallic Materials Properties Development and Standardization (MMPDS) Handbook (formerly Military (MIL) Handbook 5)

o. ASME Boiler and Pressure Vessel Codes, Section II and VIII, Div. 1 and 2

p. ASME Codes for Process Piping, B31.3 (sections as applicable, per LaRC Pressure Systems SPE)

q. NPD 8710.5, “Policy for Pressure Vessels and Pressurized Systems”

r. NASA-STD-8719.17, “NASA Requirements for Ground-Based Pressure Vessels and Pressurized Systems (PVS)”

s. MIL-HDBK-17, Composite Materials Handbook

t. Applicable Department of Transportation Regulations

u. Machinery's Handbook (Industrial Press, Inc)

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

2.3 MATERIAL SELECTION

2.3.1 **Standards:** Materials shall be selected using mechanical or other physical properties from experimental test data or the latest issue of recognized standards for the specific test regime applicable.

2.3.1.1 Minimum properties, when available, shall be used rather than nominal or typical properties.

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

2.3.3 **Material Properties Verification:** Materials used for critically stressed components or those materials subject to nonstandard or special processing shall have as-built properties verified at test temperature.

2.3.4 In particular, for cryogenic applications, tensile and fracture toughness tests shall be performed to measure strength and toughness against expected values.

2.3.5 **Galling**: Galling and galvanic corrosion shall be a prime consideration for material selection for models and all ancillary systems (e.g., sting).

2.3.5.1 Galling occurs when there is a lack of lubrication, lack of oxide film, mating surfaces with high contact pressure, mating surfaces with high polish, mating surfaces with similar hardness, and high heat. If any of these conditions exist, verification that the existing stresses do not exceed the galling threshold stress shall be determined.

2.3.5.2 Galvanic corrosion is not generally a problem during the short-duration testing of a wind tunnel model, but for ancillary systems or models exposed to saltwater/salt air, high heat, or continuous electrical charges, it is a factor. Steps shall be taken to assure compatible nobility of mating materials (difference in anodic index). When this is not possible, use of passivation for stainless steels or coating applications for other materials is recommended. For harsh environments, cathodic protection may be required.

2.3.6 **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.

2.3.6.1 The material shall have a documented fracture toughness value that exceeds 65 ksi (in.)^{½} at the operating temperature.

2.3.6.2 Acceptable documentation shall include K_{Ic} test data on the material obtained by the manufacturer using ASTM E399.

2.3.6.3 If the manufacturer does not have 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 shall include two independent sources of data and come from a reputable source, such as those defined in Section 2.3.7. However, alloys with fracture toughness values less than 65 ksi (in.)^{½} may be acceptable provided that the fracture mechanics analysis performed according to Section 2.4.4 proves that the design life is adequate.

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

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

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

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

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

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

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

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

2.4 STRUCTURAL ANALYSIS

2.4.1 **Stress Analysis:** A stress analysis shall be provided as a part of the Model Systems Report (see Chapter 5). It is to be complete and sufficiently comprehensive to require no further explanation. A discussion of a suggested format for a Stress Report that meets all requirements below is given in Appendix E:

a. The stress analysis shall show that allowable stresses are not exceeded for the worst case loading(s).

b. 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.

c. The general equations and their sources shall be given before substitution of numerical values.

d. 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.

e. Where finite element analysis methods are used for model systems analysis, the documentation shall include computer-generated plots of the finite element models, tabular or graphical summary of stress data, and detailed information on how the finite element models were verified/validated.

(1) Validation of finite element models shall be by closed form solutions, equilibrium checks, boundary condition checks, and convergence accuracy of solutions.

(2) Handbook analysis can be used as a method of validation for finite element analysis. Such analyses do not have to be made at the peak stress point, but can be used in an area of the structure that is well-suited for hand analysis.

(3) In addition, the quality of finite element modeling shall be checked by keeping mesh refined and checking for peak stress to converge when plotted by iteration number.

(4) Other checks include checking for large stress/strain gradients between shared nodes and through elements.

(5) Mesh refinement in high-stress areas shall be done to at least 5 percent accuracy.

(6) High-stress areas shall be identified and documented, along with detailed information on how the finite element models were validated for accuracy.

f. Dimensional tolerances, potential model installation errors, and potential local flow conditions shall 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) that are normally intended to be aerodynamically unloaded, the above misalignments are determined to be less than +/-2 degree, then a misalignment of at least +/-2 degree with respect to the free stream shall be used.

g. Loads caused by pressure differences due to unvented cavities shall be considered.

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

2.4.3 **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 selecting proper materials, keeping stress concentrations to a minimum by avoiding sharp discontinuities, using generous radii, and so forth. Appendix C is provided as a guide for performing fatigue design analysis and for determining the allowable oscillating stress based on model system design life requirements.

2.4.4 **Fracture Analysis:** A fracture mechanics analysis shall be 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. Details regarding performing a fracture analysis are provided in Appendix D. Three levels of analysis are presented in Appendix D, which will satisfy the fracture analysis criteria as described in this document.

2.4.5 **Design Life:** The RPE/TE shall specify the design life requirements for the fatigue and/or fracture analysis for model system components (See Section 2.10.5 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:

a. **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.

b. **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.

(1) For wind tunnel models, there is no statistical database for predicting unsteady loads as they are usually model and/or tunnel dependent.

(2) In cases where significant unsteady loads (>50 percent of steady-state) may be possible, then on-line monitoring of dynamic loads shall be required.

(3) In cases where the 25% rule provides very low unsteady load estimates (ex: for test article settings close to zero-lift angles), best effort shall be made to estimate such loads based on facility flow unsteadiness levels and flow angularity fluctuations.

(4) Once an unsteady load history is established during testing, the design shall be reevaluated for fatigue life.

2.5 MECHANICAL CONNECTIONS

2.5.1 Structural Joints:

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

2.5.1.2 **Bolted Joints:**

a. Bolted joint design shall satisfy the allowable stress criteria as set forth in Section 2.6.2 and may require independent evaluations of the strength of the joining components, particularly if dissimilar materials are involved.

b. 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 2.5.2).

2.5.2 Threaded Fasteners:

a. In general, the length of thread engagement shall be at least one time the nominal diameter of the fastener if the tapped hole material is greater than 120 ksi ultimate tensile strength.

b. For tapped holes in materials of less than 120 ksi ultimate tensile strength, a thread engagement of 1.5 times the nominal diameter of the fastener shall be used.

c. If less than 1.5 times the nominal diameter of the fastener thread engagement is used, the minimum shear strength of the threads in the joint shall be at least 4/3 times the bolt preload.

d. The length of thread engagement shall be sufficient to develop the full bolt strength without stripping either the internal or external threads. A recommended method to calculate this length can be found in the Machinery's Handbook. This method considers thread geometry and the material strengths of both the fastener and the tapped hole.

e. Bolted joints shall not rely on friction to transmit loads or maintain necessary alignments.

f. 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 meet the allowable shear stress criteria as specified in Section 2.6.2.

g. 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.

h. Preloads: Threaded fasteners shall be torqued to produce a preload equivalent to 75 percent of the yield strength of the weaker material, (either the fastener or the material comprising the threaded hole) unless a lower preload is required due to thermal or mechanical considerations.

i. The preload shall provide a clamping force of at least 1.5 times the maximum expected separating force in any of the fasteners. The manufacturer's recommended torque may be used provided the required clamping force is achieved.

j. Factor of Safety: The factor of safety for the fasteners is the appropriate load rating for the fastener, in accordance with Section 2.6.2, divided by the external load for the fastener, and shall be greater than or equal to 4 on ultimate and 3 on yield.

k. Retention: In addition to torqueing 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 installation torques are preferred.

2.6 METALLIC MATERIALS ALLOWABLE STRESS

2.6.1 **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 the stress design allowable:

a. Methods 1 and 1A are based on conventional conservative approaches, which can be employed where structural design optimization is not a factor and minimum analysis effort is needed.

b. Method 2 is a systematic approach, which can yield a more optimal structural design and, where necessary, can be used to design to lower safety factors because it requires a more rigorous analysis.

c. 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, some parts of the model system may be designed to the allowable of Methods 1 or 1A while other parts may be designed to the allowable of Method 2.

2.6.2 **Method 1:**

a. For standard handbook analysis, the allowable compound stress (axial plus bending) shall be 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.

b. In this method, the compound stress to be compared to the allowable shall be calculated for the worst combined load cases (mechanical plus thermal) and include stress concentration effects.

c. If published shear strengths are available, allowable shear stresses shall meet the preceding safety factor requirements with respect to shear ultimate and yield strengths.

d. In the absence of shear strength data, the maximum allowable shear yield stress for all combined loads shall 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.

e. When using the von Mises stress theory, the maximum allowable shear stress is $\tau = S_Y / \sqrt{3}$ consistent with the von Mises failure theory, with a required safety factor of 3.

2.6.3 Method 1A:

2.6.3.1 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.

2.6.3.2 Method 1A 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, shall be applied to show that fatigue failure is not a problem by performing a fatigue or fracture analysis as per Section 2.4.3 or 2.4.4, respectively.

2.6.4 Method 2:

2.6.4.1 This method can be used when the system cannot be designed to the allowables of Methods 1 or 1A.

2.6.4.2 However, in order to design to the allowables in this section, the stress state in the model system structure shall be well understood to a high level of confidence. Closed-form solutions and standard handbook calculations will, in many cases, suffice.

2.6.4.3 All contributions to stress shall be included in the calculations. However, for highly 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:

2.6.4.3.1 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.** This method does not cover bolt stresses (see Section 2.6.2).

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 (σi, σj, σk):** The stress normal to the plane of reference.

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

(4) **Membrane Stress (σ_m):** 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) necessary to satisfy the simple laws of equilibrium of external and internal loads. 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 (σ_s):** 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 (σ_p):** 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 causes no 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 non-uniform 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 producing 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, then returns to the initial value. A single operational cycle may result in one or more stress cycles.

b. **Calculation of Combined Principal Stress:**

(1) At the point on the structure that is being investigated, choose an orthogonal set of coordinates (i,j,k).

(2) The stress components in the directions are then designated σi, σj, σk for normal stresses and τij, τjk, τki for shear stresses.

(3) 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:

(a) General primary membrane stress, σ_m

(b) Primary bending stress, σ_b

(c) Secondary stress, σ_s

(d) Incremental peak stress, σ_p

(4) 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:

σ_{12} = abs(σ_1 - σ_2) **NOTE:** For a biaxial state of stress $\sigma_3 = 0$.

σ_{23} = abs(σ_2 - σ_3)

σ_{31} = abs(σ_3 - σ_1)

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

c. **Combined Stress 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:

$^1/_2$F1*S_y or $^1/_3$ S_u

where

S_y = minimum specified yield strength

S_u = minimum specified ultimate strength

and

F_1 = (.8)[2 - S_y/ S_u], 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:

$^2/_3$ S_y or $^1/_3$ S_u

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

$$\sigma_m + \sigma_b \le \alpha S_m$$

α = shape factor = $^{Z \text{ (plastic modulus)}}/_{S \text{ (elastic modulus)}}$, ≤ 1.5 for the section in bending.

α = 1.5 for rectangular sections, plate and bar

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

$$\sigma_m + \sigma_b + \sigma_s \le 2.0Sm$$

(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 2.4.3).

$$\sigma_\mathrm{m} + \sigma_\mathrm{b} + \sigma_\mathrm{s} + \sigma_\mathrm{p} \le \mathrm{S_a}$$

The allowable stresses are summarized in the following table:

Table 2-A. Combined Stress Allowable Values.

Combined Stress Intensity	Tabulated Value	Yield		Ultimate	
		Most Metals	Austenitic SS and Nickel Alloys	Most Metals	Austenitic SS and Nickel Alloys
σ_m	S_m	$^1/_2\ S_y$	$^2/_3\ S_y$	$^1/_3\ S_u$	$^1/_3\ S_u$
$\sigma_m+\sigma_b$	αS_m (if α = 1.5)	½ αS_y ($^3/_4\ S_y$)	$^2/_3\ \alpha S_y$ (S_y)	$^1/_3\ \alpha S_u$ ($^1/_2\ S_u$)	$^1/_3\ \alpha S_u$ ($^1/_2\ S_u$)
$\sigma_m+\sigma_b+\sigma_s$	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	…	…	…	…

2.6.4.3.2 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, τ_{xy}, τ_{xz}, τ_{yz}) as a single invariant stress, independent of the coordinate system. 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 only normal (principal) 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:

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

b. **Bi-Axial Stress State:**

For stress states where there are normal stresses 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:

Table 2-B. Von Mises Theory Allowable Values.

	Localized Peak Stress		**Net Section Stress**	
Calculated Value	**Yield Strength**	**Ultimate Strength**	**Yield Strength**	**Ultimate Strength**
σ_e	S_y	$^2/_3\ S_u$	$^2/_3\ S_y$	$^1/_2\ S_u$

2.6.5 **8’HTT Model Requirements**:

2.6.5.1 The 8’HTT at LaRC is a high energy facility with little chance of facility damage when model parts fail. When the allowables of this section cannot be met for hardware to be used in this facility, the hardware can still be tested by utilizing the deviation procedures listed in Chapter 6.

2.6.5.2 The customer shall conduct a reasonable effort to accurately predict the stresses imposed on their model when subjected to the normal test conditions and unstart conditions in the 8’HTT. This is usually done in concert with facility experts.

2.6.5.3 It is highly desirable from all points of view that the model be capable of withstanding the run and unstart loads with the safety factors required of other facilities. However, it is understood that for many research components, these high factors of safety cannot be attained without significant compromises to the test objectives.

2.6.5.4 Many test articles will have low factors of safety when subjected to the facility thermal and pressure loads. In these cases, the customer shall accept the risk to the model under the load condition, documented via formal memo acknowledging the known risk to the model.

2.6.5.5 The facility’s customers shall conduct the appropriate stress analyses and submit their analyses to NASA’s Model Systems Engineer (MSE).

2.6.5.6 The MSE may offer some assistance to the customers regarding design changes that would increase the safety factor(s). Ultimately, the decision to test an article with low margin shall be reached jointly between the Facility Systems Engineer (FSE), the test customer, and the FSH.

2.6.5.7 The final decision to test shall balance the risk to the facility and the risk to the customer’s model.

2.6.5.8 The group’s decision shall be signed off by the LaRC organization director of the facility and by the customer’s program manager.

2.6.5.9 It is permissible to test models with low factors of safety because there are no fragile or intricate components downstream of the test section. Because the facility downstream components are simple in design, it is reasonable to expect that any impact caused by a model component breaking away and traveling out of the tunnel would not be difficult or expensive to repair.

2.7 NONMETALLIC AND RAPID PROTOYPING MATERIALS ALLOWABLE STRESS

2.7.1 **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.

2.7.1.1 The glass- or graphite-based composite materials used for models shall be limited to laminates having quasi-isotropic stacking sequences.

2.7.1.2 The glass- or graphite-based composite materials 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 ($\varepsilon \geq 0.0015$ in/in).

2.7.1.3 Fatigue analyses using an appropriate and documented criterion shall be performed where applicable.

2.7.1.4 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.

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

2.7.2 **Wood:** The orthotropic nature of the mechanical properties of wood as well as environmental effects shall 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.

2.7.3 **Glass:** Due to the brittle nature of glass, the allowable stress is 1/10 the material ultimate strength.

2.7.4 Other materials shall be dealt with on an individual basis.

2.7.5 **Rapid prototyping Materials:** Rapid prototyping can take many forms: fused deposition modeling (FDM), laser sintering, Stereo Lithography (SLA), and others. They produce parts of varying degrees of accuracy and strength, typically in one thin layer at a time. Their advantages are intricacy and speed.

2.7.5.1 Materials used for these processes run the gamut from paper and cornstarch to high-strength steels. The most common materials for wind tunnel models are plastics and steels.

2.7.6 Inherent in all of these processes is the layering and the resultant non-homogeneous nature of the material. This results in anisotropic behavior in the material properties. Couple this with the variables in the manufacturing process (laser power and dwell time for SLA, raw material purity, layer thickness, nozzle size for deposition, etc.) and one gets as-built properties that are highly dependent on the build direction. Variations have been seen with ratios of weakest direction to strongest direction up to and past 1:3.

2.7.7 When used for small, trivially stressed detail parts, these differences are of not much importance, and these parts can be used with minimal analysis and testing. But when used for structural applications, the property variability is naturally of extreme importance. Because of these possible differences, one cannot use the manufacturer's published typical strength values. Samples shall be made alongside each part, with the same representative build orientation.

2.7.8 When first using a new process, machine, or supplier, the samples shall be built in three build directions: flat, 45°, and upright.

2.7.9 These samples shall then be pulled to obtain rudimentary strength properties for the different build directions. For critical applications this may include dynamic testing for ductility and fracture properties (e.g., Charpy and crack growth testing).

2.7.10 In parts that are loaded in various directions relative to the build direction, the lowest strength values shall be used, with the required factors of safety dependent on the analysis method (Section 2.6).

2.7.11 As a particular process is used and more history with the producer and machine is established, the samples need not be tested, but they shall still be made and controlled as any other material samples for the model. When a process is changed (e.g., new machine, new raw material, different machine settings), the sample requirement resets.

2.7.12 For critical applications, a much more extensive test program is required. This program is dependent on the manufacturing process used, the history of the part producer with the process, and the projected test environment (elevated or depressed temperatures, high vibration, etc).

2.7.13 The tests on the material samples shall be done in the same environment the model will be subjected to.

2.7.14 Exact requirements shall be established on a case-by-case basis by the FSH, along with the MSE and the TE.

2.7.15 Materials engineers shall be consulted as required to assure that all pertinent material attributes are verified and all appropriate material post processing has been completed (such as solution annealing to remove residual stresses).

2.8 STABILITY

2.8.1 **General:** When the model system is to be analyzed for stability, rigid body motions shall be considered about all axes, with flexibility about pitch, roll, and yaw axes considered for aeroelastic stability.

2.8.2 **Divergence:** A safety factor of 2 against divergence shall be used 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 satisfied if the increase in load due to the increase in angle-of-attack ($\Delta N/\Delta\alpha$) under the effect of normal force does not exceed one-half of the restoring force generated by the elasticity (stiffness) of the model support system generated by such an angle change ($\Delta F/\Delta\alpha$). This paragraph is not applicable to models that are tested for divergence.

2.8.3 **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.

2.8.4 **Dynamics:** Models to be dynamically tested shall be analyzed to show that the mountings and/or emergency restraints are structurally adequate and dynamically stable.

2.8.5 **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

2.9.1 All pressurized model systems inside and outside the model are to be designed and fabricated according to the following codes:

a. ASME Boiler and Pressure Vessel Code Section VIII and Section II

b. ASME B31.3, “Process Piping Code”

c. LPR 1710.40, “Langley Research Center Pressure Systems Handbook”

2.9.2 Relief devices shall be required in the supply system, but not necessarily in the model.

2.9.3 Relief devices shall be capable of discharging the full flow of the pressure source under all conditions.

2.9.4 Pressure systems inside the model, which have the maximum pressure times the maximum projected area of the pressurized surface less than 7,000 pounds, shall 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.

2.9.5 In addition to the design requirements specified in Section 2.9.3, pressure testing of pressure systems shall be required where feasible:

a. Hydrostatic testing of pressure systems is the preferred method of pressure testing. Test pressure shall 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. Hydrostatic testing is potentially hazardous. Adequate safety precautions shall be taken to ensure safety of personnel and equipment with regard to test procedures.

b. After hydrostatic testing, components shall be dried appropriately.

c. 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 shall be used. Unless circumstances demand a reduced test pressure, the test pressure shall be no less than 1.5 times the design pressure times the ratio of the material strength at pneumatic test temperature to the material strength at design temperature. Pneumatic testing is inherently dangerous, and all personnel shall be excluded from a predetermined hazard zone.

d. Pneumatic testing shall conform to the testing requirements set forth in LPR 1710.40.

2.10 ROTATING SYSTEMS

2.10.1 **General:** The special requirements set forth in this Section apply to model systems that 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.

2.10.2 **Design for Normal Operation:**

a. 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.

b. 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.

c. 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 2.10.7).

d. Propeller model drive systems shall be designed to operate at 20 percent overspeed.

e. Rotor model systems shall be designed to operate at 10 percent overspeed.

f. Fasteners, which are designed to carry loads associated with rotation, shall be secured by mechanical locking (see Section 2.5.2(j)).

g. Such fasteners shall include not only those securing rotating parts but also all fasteners that translate rotational loads back to the test bed. For example, fasteners that hold the pylon to the nonrotating parts, such as a nacelle, and to the model fuselage fall into this category.

h. Provisions shall be made for balancing the system (see Section 2.10.6).

i. Bearing life and lubrication requirements shall be specified for the expected operating environments.

j. 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.

2.10.3 **Design for System Failure Event:** Models shall be designed such that after an initial failure, no further failure occurrence will cause facility damage during the tunnel shutdown process (that is, ultimate safety factors are greater than 1.0 when unbalanced loading is considered).

a. Propeller model system unbalance loads shall be calculated as follows: For an even number of blades, design for loss of one-half 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.

b. Rotor model systems shall be designed to sustain the loss of one blade.

c. For both propeller and rotor models, particular model configurations may require the consideration of simultaneous blade failure on multiple hubs.

d. For both propellers and rotors, blade 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.

e. 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.

f. Whenever appropriate, the effects of bearing failure shall be considered.

g. 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 deviation might be tunnel features that reduce risk (for example, low free-stream 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 shall be informed as soon as possible that such a request is being contemplated.

2.10.4 **Analysis:**

a. 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 2.10.5(d)).

b. Dynamic stability analyses will be required only if specified by the RPE/TE or FSH.

c. The provisions of Section 2.4 (with the exception of Sections 2.4.5(a) and 2.4.5 (b)) shall apply to all rotating components. All of Section 2.4 applies to the nonrotating components in the model.

2.10.5 **Structural Testing:** The RPE/TE or FSH shall establish acceptance criteria based on the following requirements:

a. **Propeller Blades:** One blade from each manufactured set of propeller blades shall 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 that simulates the critically loaded part of the blade (for example, the root portion of the blade).

b. **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 that simulates the critically loaded part of the blade.

c. Frequency response checks shall be made while each blade is clamped in a fixture at the root. The frequency checks are to be used to determine that the blades are structurally similar by comparing the first mode (usually bending or torsion) frequency and damping characteristics.

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

2.10.6 **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.

2.10.7 The assembled propeller or rotor system, excluding rotating controls or instrumentation wiring, shall be either statically or dynamically balanced such that the imbalance force does not exceed the magnitude of that oscillatory force for which the highest critically stress component of the system will have “infinite” fatigue life.

a. For static balancing, the imbalance force F is given by the relationship

$$F = \left(\frac{S_u}{g}\right)\Omega^2$$

where S_u is the measured maximum static imbalance about the rotational axis, Ω 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 Ω, and in./sec^2 for g.)

b. 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.

2.10.8 **Demonstration Testing:** Demonstration run-up testing of the model system (test configuration) shall be performed 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.

2.10.9 Demonstration 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.

2.10.10 **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.

2.10.11 Specific inspection requirements shall be established by the TPE/TE/RPE.

2.11 NONDESTRUCTIVE EVALUATION

2.11.1 All materials used for critically stressed components for cryogenic model systems (excluding fasteners) shall be subjected to 100 percent volumetric nondestructive evaluation (NDE).

2.11.2 Non-cryogenic model systems NDE requirements shall be established by the TPE/TE/RPE:

2.11.3 **Metals:**

a. Surface contact or immersion NDE methods may be used for ultrasonic inspection.

b. Liquid penetrant, magnetic particle, or eddy current inspection method may be used for surface inspections.

c. 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.”

d. Radiographic and surface inspection standards and specifications are given in Section V of the ANSI/ASME Boiler Pressure Vessel Code.

e. At a minimum, surface inspection shall be performed on critically loaded, final machined components in areas that have the potential for crack formation.

2.11.4 Composite Material Inspection:

a. Translucent visual inspection, as defined in ASME Code Section V, Articles 9 & 28, shall be used (where possible) during fabrication to check for delaminations, inclusions, contaminations, fiber orientation, and other defects.

b. All critically loaded composite components shall be examined by both visual and ultrasonic methods for the final inspection.

c. No cracks, delaminations, disbonds or other structurally significant defects shall be 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.

2.11.5 Inspection Personnel:

a. All inspection personnel shall be certified to Level II of the recommended practice of ASNT Publication SNT-TC-1A or its equivalent.

b. Inspectors who perform tap tests shall 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 shall 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 ACCEPTANCE OF MODEL SYSTEMS FOR TESTING

2.13.1 **Previous Tests:** Models previously tested in the same and/or other facilities may be tested at LaRC with FSH approval. The request for approval shall include, at a minimum, documented evidence that:

a. The model was tested to loads equal to or higher than those anticipated in the proposed test.

b. A fatigue evaluation that demonstrates the design life of the model will not be exceeded during the LaRC tests.

c. Critically stressed components will undergo NDE prior to wind tunnel testing.

2.13.2 **Static Load Tests:** With FSH approval, static load tests may be conducted in lieu of stress analysis. These tests are to be based on worst load case(s) and indicate no permanent deformation when carried to either:

a. 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 shall be included in the Model Systems Report.

b. 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.

2.13.3 **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 shall approve the acceptability of models and/or components to be tested and/or used under the provisions of this section.

2.14 FORCE BALANCE DESIGN AND IN-SERVICE INSPECTIONS

2.14.1 **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:

a. For a force balance utilizing Method 1 or 1A, the allowable stresses shall be determined according to the same criteria as described in Sections 2.6.2 and 2.6.3 (smaller of $^1/_4$ of the minimum ultimate strength or $^1/_3$ of the minimum yield strength of the material).

b. Since the stress state in the model system structure shall 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 2.6.4 may be used to determine the combined stress intensity allowables.

c. 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.

d. 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.

2.14.2 **Fatigue and Fracture Analysis:**

a. The highest stress points in the balance (for example, in the stress concentrations where crack initiation and growth would most likely occur) shall be identified and documented in the Balance Stress Analysis Report as control points for fatigue and fracture analysis and periodic in-service inspection.

b. Fracture analysis shall be required for cryogenic balances.

c. For a particular balance, the balance design review panel shall determine the fatigue analysis requirements (which may deviate from Appendix C) and the fracture analysis requirements (which may deviate from Appendix D).

2.14.3 **Failure Modes Analysis:** A failure modes analysis shall be performed to establish single and/or multiple point failures that could result in model loss, with the analysis and its results documented in the Balance Stress Analysis Report.

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

2.14.5 **Testing Frequency:** As a minimum, each balance shall be loaded to its combined load limit as defined in paragraph 2.14.4 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.

2.14.6 Such load tests shall assure that all beams (flexures) and critically loaded components are intact and undamaged.

2.14.7 **Inspections:** All balances shall be thoroughly inspected at time of manufacture, and at the same established intervals detailed in paragraph 2.41.5 for the presence of surface and internal cracks and defects, particularly in areas of stress concentrations and the control points as identified in 2.14.2.

2.14.8 Inspection requirements as a minimum shall include a visual microscopic inspection and a comparison of the unloaded balance electrical outputs.

2.14.9 Other specific inspection requirements shall be the responsibility of the Force Measurement Engineer (FME).

2.14.10 **Design Evaluations for Non Accessible Balances:** For balances in which the control points specified in 2.14.2 cannot be inspected without complete disassembly or are inaccessible due to the geometry of the balance, a thorough evaluation of the design shall be performed for certification of tunnel use.

2.14.11 The evaluation shall include:

a. Fatigue life assessment considering past usage history (where available) based on stresses at the control points.

b. A containment system shall be identified which provides model retention in all failure modes of the balance identified in 2.14.3.

c. In the absence of sufficient information to perform the assessments in paragraphs a and b, the FME shall derate the balance to establish safe working levels.

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

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

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

2.14.15 **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:

a. **Previous Tests:** Balances previously tested in the same and/or other facilities may be tested at LaRC. The request for approval shall include documented evidence that each of the three following conditions are satisfied:

(1) The balance 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 balance shall not be exceeded during the LaRC test.

(3) Critically stressed components shall undergo NDE prior to wind tunnel testing.

b. **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 shall be included in the Balance Stress Analysis Report.

2.15 AUTOMOTIVE VEHICLES

2.15.1 **General:** The special requirements set forth in this section apply to wind tunnel testing of automotive vehicles. These vehicles are primarily designed for roadway use. They may be tested in the LaRC wind tunnels if the following criteria are met. In situations where these criteria are not clear, the FSH may determine the appropriate criteria and document the determining rationale.

2.15.2 **Vehicle integrity:**

a. The preferred method of certifying a vehicle for testing is compliance with the stress analysis methods described in Chapter 2 of this LPR. However, if this cannot be done satisfactorily, the vehicle shall have been road/track driven with the baseline configuration and all significant permutations of the model changes to be accomplished.

b. The road/track test shall be at the maximum test speed for at least one minute without component deterioration or failure.

2.15.3 **Vehicle Inspection:**

a. The vehicle shall be routinely inspected during each tunnel access.

b. Items judged to be worn and/or at-risk fasteners and fastening methods shall be corrected to continue testing.

c. All components shall fit tightly.

d. All loose components inside the automotive vehicle shall be removed to prevent them from entering the air stream.

2.15.4 **Vehicle De-Fueled:**

a. The vehicle shall be de-fueled to a level consistent with only unusable fuel remaining in any fuel tank, hose, or fuel supply routing. Fuel leaks, visible or detected by olfactory methods, are not permitted.

b. A Safety Data Sheet (SDS) of the fuel shall be provided and the LaRC Fire Chief notified before the wind tunnel test starts.

c. Any proposed vehicle running tests shall include the LaRC Fire Chief as an additional approver in the waiver approval process.

2.15.5 **Batteries:** The preferred method of testing is to remove all batteries from the vehicle. However, if batteries are an integral part of the testing system, the type of battery and method of fusing the battery circuit shall be examined by the FSH for safe installation practices. An emergency battery disconnection method may be requested to be demonstrated by the TE.

2.15.6 **Corrosive Chemicals:** All corrosive chemicals considered dangerous to common human contact or inhalation shall be removed from the vehicle prior to wind tunnel testing.

2.15.7 **Compressed Gases:** All compressed gas (flammable or inflammable) cylinders shall be removed from the vehicle unless demonstrated to be completely empty of pressure. This includes fire suppression systems.

2.15.8 **Vehicle Securing Systems:** Two methods of securing the vehicle in the tunnel shall be used:

a. A brake pedal locking device shall be installed in the vehicle as one method.

b. The second method may include incorporating tire restraint straps to the tunnel floor or a cable secured to the undercarriage with a factor of safety of 2 based on predicted maximum drag force of the vehicle.

2.15.8.1 In addition, brake fluid levels and restraint strap condition shall be inspected before each day’s test and upon tunnel entry during the test.

2.15.9 **Vehicle Fluids:** Common vehicle fluids such as motor oil, hydraulic fluid, and antifreeze/water are permitted. Any leaks of these fluids onto the tunnel floor or into the air stream shall halt the test until promptly cleaned up and source stopped.

2.15.10 **Developing Risks:** Any situation deemed to be an unacceptable risk by the TE shall be examined by the FSH for consideration of a solution.

CHAPTER 3: CERTIFICATION OF STINGS AND OTHER MODEL MOUNTING HARDWARE AND GENERAL PERIODIC IN-SERVICE INSPECTIONS OF MODELS

3.1 INTRODUCTION

3.1.1 All models and model support hardware, including stings, knuckles, and other pieces of equipment, shall be inspected on a regularly scheduled basis.

3.1.2 If a part is critically loaded, an inspection criterion shall be determined during the design stage.

3.2 NEW STING AND MODEL MOUNTING HARDWARE

3.2.1 Maximum load limits based on allowable design stresses shall be established for each sting and other model mounting hardware.

3.2.2 The sting and associated hardware shall be inspected at the time of manufacture and at least once per year during usage.

3.2.3 New 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.

3.2.4 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.

3.2.5 Specific inspection requirements shall be established and documented by the RPE/TE/TPE and/or FSH.

3.2.6 Documentation of inspection requirements shall be included in the Model Systems Report.

3.3 EXISTING EQUIPMENT

3.3.1 Maximum load limits based on allowable design stress shall 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.

3.3.2 Existing 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.

3.3.3 The stings and associated hardware shall be inspected for the presence of surface cracks and signs of wear or defects, particularly in areas of stress concentration.

3.4 GENERAL PERIODIC IN-SERVICE INSPECTIONS OF CALIBRATION MODELS AND OTHER MODEL HARDWARE

3.4.1 Calibration model systems and other model system components, such as lifting surfaces, flaps, fasteners, and so forth, may require periodic inspection to guard against fatigue failure.

3.4.2 Surfaces and areas that may require inspection shall be identified and inspection requirements specified by the RPE/TE/TPE and/or FSH.

3.4.3 Inspection requirements shall be documented and included in the Model Systems Report.

3.5 MECHANICAL CONNECTIONS OF STING TAPER JOINTS

3.5.1 All new sting hardware utilizing taper joints shall not be accepted for initial testing in a wind tunnel with less than 80 percent contact on the taper.

3.5.2 All existing sting hardware utilizing taper joints shall not be accepted for initial testing in a wind tunnel with less than 75 percent contact on the taper.

CHAPTER 4: QUALITY ASSURANCE

4.1 INTRODUCTION

4.1.1 This chapter provides detailed quality assurance criteria for wind tunnel model systems to be tested at LaRC.

4.1.2 These criteria are intended to ensure that the as-built model system hardware meets the model system design specifications.

4.2 IMPLEMENTATION RESPONSIBILITY

4.2.1 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.

4.2.2 Components (including fasteners) are defined as critically loaded/stressed when their failure can result in critical or catastrophic facility damage/injury, as defined in LPR 1740.4, "Facility System Safety Analysis."

4.2.3 Responsibility for determining specific quality assurance requirements and compliance for the different categories of model systems is assigned as follows: At a minimum, components identified as critically loaded/stressed 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 criteria given in this chapter provide the basis for judging the adequacy of user-furnished model systems quality assurance implementation.

(1) The user shall furnish documentation that gives evidence of compliance with the intent of this chapter.

(2) This documentation shall be included in the Model Systems Report (see Chapter 5) submitted to the FSH.

(3) The RPE/TE shall be responsible for ensuring that the report meets the requirements of this document.

4.3 QUALITY ASSURANCE CRITERIA

4.3.1 Procurement:

a. **Purchase Orders:** All purchase orders (see LMS-CP-4505, "Purchase Requisition (PR) Initiation/Modification/Cancellation and Supporting Documentation") for model systems parts and materials, including fasteners and pins, shall identify procurement quality assurance and inspection acceptance criteria.

b. **Receiving Inspection:** Receiving inspection and acceptance of hardware and all documentation thereof shall be the responsibility of the TPE/ RPE/TE ordering the hardware.

(1) When requested or required, receiving inspection shall 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.

(2) Upon completion of receiving inspection, all supplier data documentation shall be maintained by the QAS and delivered with the hardware.

c. **Acceptance/Rejection of Procured Articles:**

(1) The documentation of articles and materials shall 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.

(2) Articles that do not conform to drawings or specifications and/or do not have adequate or correct data shall be held for disposition.

d. **Supplier Documentation**: Evidence of the following required supplier inspections and tests, as defined in the purchase documentation, shall be verified at receiving inspection:

(1) Material certification test report

(2) Evidence of supplier inspection acceptance

(3) Certification of heat treatment process

(4) Certification that the end-item is from the material specified

(5) Test data

(6) Inspection reports

(7) Weld and Braze Qualification/Certificiation documentation as required by the purchase order

(8) Other documentation as specified on the purchase order

e. **Model Threaded Fasteners and Pins:** All safety critical products (including critical fasteners, pins, etc.) shall follow the guidelines set forth in both LAPD 4520.1, "Langley Research Center Requirements for Safety-Critical Products," and LAPD 5330.3, "Langley Research Center (LaRC) Standards for the Acquisition and Use of Threaded Fasteners."

4.3.2 **Fabrication:**

a. **Traceability and Control:** Raw materials and parts used in the fabrication and assembly of model systems shall be controlled to maintain identification and traceability.

b. **Controlled Storage:** Critical raw materials, parts, and fasteners shall be stored in a dedicated, controlled-access storage area.

c. **Configuration Control:**

(1) Configuration of the end-item hardware shall be maintained by the TPE/RPE/TE through the control of drawing and specification changes per LPR 7320.1.

(2) The TPE/RPE/TE shall be responsible for assuring that obsolete drawings/specifications are withdrawn and destroyed per LPR 7320.1.

d. **Identification:**

(1) When possible, model system hardware shall be identified by electrolytic etch, or other methods that may be appropriate, on a surface location that will not affect flow or structural integrity.

(2) 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, shall be specified on the drawing.

(3) The model identification shall be posted on the model's container.

e. **Drawing and Specification Control:** Drawings and specifications shall define the complete as-built configuration and provide a record of the design.

(1) All drawings, specifications, and subsequent revisions shall be reviewed by the TPE/RPE/TE.

(2) A copy of all revised drawings shall be provided to the fabrication quality organization for use in the final inspection of the hardware.

f. **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 shall be initialed and dated on the face of the fabrication drawings prior to implementation.

4.3.3 **Fabrication/Inspection Plan:** If required, the TPE/RPE/TE shall be responsible for coordinating the fabrication and inspection effort with the fabrication Lead Technician and the QAS.

4.3.4 The manufacturing planning shall be documented on the LF 136, "Fabrication Inspection and Operations Sheet," per LMS-CP-5640, "Requesting, Performing, and Closing Fabrication Services Requests," or the equivalent, preferably by the Lead Technician.

a. **Content:** The Fabrication Inspection and Operations Sheet (FIOS) shall define the pre-manufacturing 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.

b. **Identification:** The FIOS shall 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 shall be considered:

(1) **Pre-Fabrication:** Receiving inspection, identification, raw material certification (including chemical composition, physical properties, NDE, 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.

f. **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 Report (NCR).” Documentation on a LF 136,”Fabrication Inspection and Operations Sheet,” per LMS-CP-5640 or an equivalent form and process may be 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. At 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.

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

h. **Handling, Packing, and Shipping:** All hardware shall be protected from damage during all phases of manufacturing and shipping.

(1) The TPE/RPE/TE shall document any special handling, packing, and shipping requirements for model system hardware.

(2) Shipping containers shall be designed to ensure safe arrival and ready identification.

(3) Containers for finished hardware shall provide identification for individual parts and shall 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 shall be incorporated into the Model Systems Reports by the TPE/RPE/TE as required by Chapter 5.

CHAPTER 5: DOCUMENTATION

5.1 MODEL SYSTEMS REPORT

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

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

5.1.3 **Contents:** The Model Systems Report shall contain, at a minimum, the following:

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

b. **Design loads:**

(1) Model specifications/requirements

(2) Derived loads (aerodynamic, mechanical, and thermal, including unsteady loads)

(3) Life requirements

c. **Stress report (See Appendix E):** The stress report, at a minimum, shall include the following information:

(1) Summary of factors of safety

(2) References (general equations, terms, codes, and computer programs)

(3) Assumptions

(4) Materials data:

(a) Standard properties

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

(c) Fasteners

(5) Method of analysis:

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

(b) Shear and moment diagrams

(c) Stress analysis for worst case load(s)

(6) Structural joint analysis:

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

(b) Welded

(c) Brazed

(d) Bonded

(7) Pressurized systems analysis (if required)

(8) Hydrostatic test results (if required)

(9) Specialized analysis (if required):

(a) Fatigue and fracture

(b) Thermal

(c) Finite Element

(d) Hazard Analysis

d. **Stability report (as required):**

(1) Divergence

(2) Flutter

(3) Dynamics

(4) Buckling

e. **Inspection reports:**

(1) Certification of materials

(2) Fabrication and Inspection Operations Sheet (if required). LF 136, “Fabrication Inspection and Operations Sheet,” LMS-CP-5640, or equivalent

(3) Inspection procedures

(4) Nonconformance reports

(5) Quality assurance report

f. **Test reports (if required):**

(1) Material properties

(2) Loads tests

(3) Modal survey

(4) Static and dynamic balancing

(5) Demonstration run-up

g. **Deviation requests and supporting documents**

h. **Single Order Failure Risks and Interlocks Analysis**

i. **Design review documents, action items, and their disposition**

j. **List of critically loaded/stressed components:**

(1) Include component failure effect on the facility and the associated Risk Assessment Code (RAC)

(2) Cross-reference appropriate quality assurance documents (e.g., inspection reports, material certifications) for components whose failure can result in a critical or catastrophic failure

5.1.4 **Retention:**

a. Each facility shall coordinate any retention requirements of any and all components of the Model Systems Report with the customer and/or program office on a test-by-test basis.

b. The TE/TPE/RPE shall be the responsible party to see that this coordination is accomplished.

5.2 ASSEMBLY, INSTALLATION, AND CONFIGURATION CHANGE PROCEDURES

5.2.1 **General:** A model system assembly, installation, and configuration change procedure shall be established as early as possible, preferably at a pretest meeting, for all model systems to be tested at LaRC.

5.2.2 **Delivery Schedule:** Documentation of the procedures shall be submitted to the LaRC RPE/TE no later than four weeks prior to the tunnel entry date, according to the schedule established by the RPE/TE.

5.2.3 **Contents:** Typical procedures and/or drawings shall 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

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

5.3.2 **Model Components:** If possible, each model component shall be marked with the drawing number assigned to that part.

5.3.3 **Model Boxes:** Each model box shall be permanently marked with the model number assigned to that model.

CHAPTER 6: DEVIATIONS

6.1 GENERAL

6.1.1 When a deviation from the requirements of this guide is considered necessary, a written request for approval shall be submitted to the cognizant FSH.

6.1.2 Approval or denial of the request shall be documented by the FSH and retained in the facility files.

6.2 DEVIATION REQUESTS

6.2.1 The deviation request shall be submitted through the TPE/RPE/TE to the cognizant FSH.

6.2.2 The FSH shall 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.

6.2.3 An information copy of all deviation requests and their disposition shall be submitted to the Safety and Facility Assurance Branch (SFAB) in the Safety and Mission Assurance Office (SMAO).

6.2.4 The deviation request shall contain, at 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

6.3.1 In instances where a model system failure could be expected to result in a risk assessment of RAC 3 or less per LPR 1740.4, the FSH shall be authorized to approve deviation requests.

6.3.2 For model system failure situations that could be expected to result in a higher risk assessment than RAC 3, but not to exceed a RAC 2, the organization director of the involved facility and LaRC Safety Manager shall approve all deviations.

6.3.3 In any instance where the risk level is expected to be higher than RAC 2 in the event of a model system failure, concurrence shall be through the LaRC Center Director.

APPENDIX A. DEFINITIONS

Catastrophic: A failure that may cause death, permanent disability, the hospitalization of three or more people, and/or system/equipment damage in excess of $1,000,000 (Type A or B Mishap).

Critical: A failure that may cause lost time injury or illness, and/or system/equipment damage between $250,000 and $1,000,000 (Type C Mishap).

Critical Speed: A speed of a rotating system that corresponds to a resonant frequency of the system.

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.

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 (FSHs are listed in the LaRC Telephone Directory.).

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.

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.

Informal Engineering Review: A review of the engineering design by personnel other than those directly involved in the model design.

Lead Technician: The fabrication technician assigned fabrication planning and coordination responsibility for the model system.

Mandatory Facility: A wind tunnel facility that shall abide by the criteria established by this document.

Model Systems: Model systems covered by this LPR are defined as models, flow survey devices, splitter plates, model support hardware including force balances (Section 2.14 only), and stings.

(1) **Exclusions:** This LPR 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 that 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.

Model 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 LPR.

Planning Meeting: A pre-design meeting usually involving research, facility, design, and instrumentation personnel with the prime objective of establishing the model systems requirements and the applicability of this LPR.

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.

Quality Assurance Specialist (QAS): The specialist assigned to support the implementation of the quality assurance requirements.

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.

Test Engineer (TE): The resident engineer at the test facility that has been assigned the test on the model/system under consideration.

Technical Project Engineer (TPE): The cognizant engineer assigned the overall responsibility for the design and fabrication of the model system.

User-Furnished Model System: Model system designed and fabricated without NASA-LaRC design review and manufacturing control.

APPENDIX B. ACRONYMS

AISC	American Institute of Steel Construction
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASNT	American Society for Nondestructive Testing
ASTM	American Society for Testing Materials
AWS	American Welding Society
CID	Center Interim Directive
CP	Center Procedure
DoD	Department of Defense
DT	Damage Tolerance
FIOS	Fabrication and Inspection Operations Sheet
FME	Force Measurement Engineer
FSE	Facility Systems Engineer
FSH	Facility Safety Head
LAPD	Langley Policy Directive
LaRC	Langley Research Center
LF	Langley Form
LMS	Langley Management System
LPR	Langley Procedural Requirements
MSE	Model Systems Engineer
NEC	National Electric Code
NCR	Nonconformance Report
NDE	Nondestructive Evaluation
NDSSGL	National Design Specifications for Stress Grade Lumber
NIST	National Institute of Standards and Technology
PR	Purchase Requisition
RAC	Risk Assessment Code
RPE	Research Project Engineer
RPV	Remotely Piloted Vehicle
QAS	Quality Assurance Specialists
SAE	Society of Automotive Engineers
SDS	Safety Data Sheet
TE	Test Engineer
TPE	Technical Project Engineer

APPENDIX C. FATIGUE DESIGN

C.1 ALTERNATING STRESS DEFINED

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

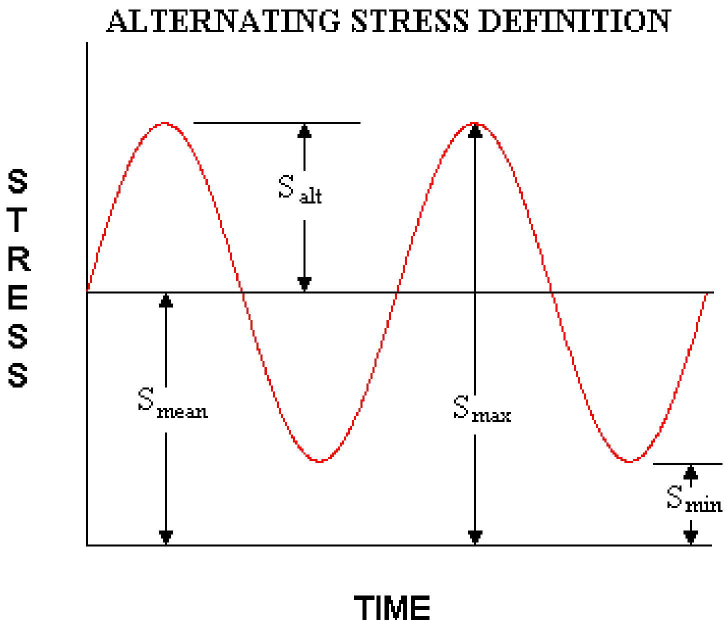

Figure C - 1. Alternating Stress Definition.

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.

C.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
$S_e \leq 0.5\ S_u$ where $S_u \leq 200$ Ksi	$S_e \leq 0.3\ S_u$
$S_e \leq 100$ 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 shall not preclude the designer from calculating the fatigue life of the system.

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

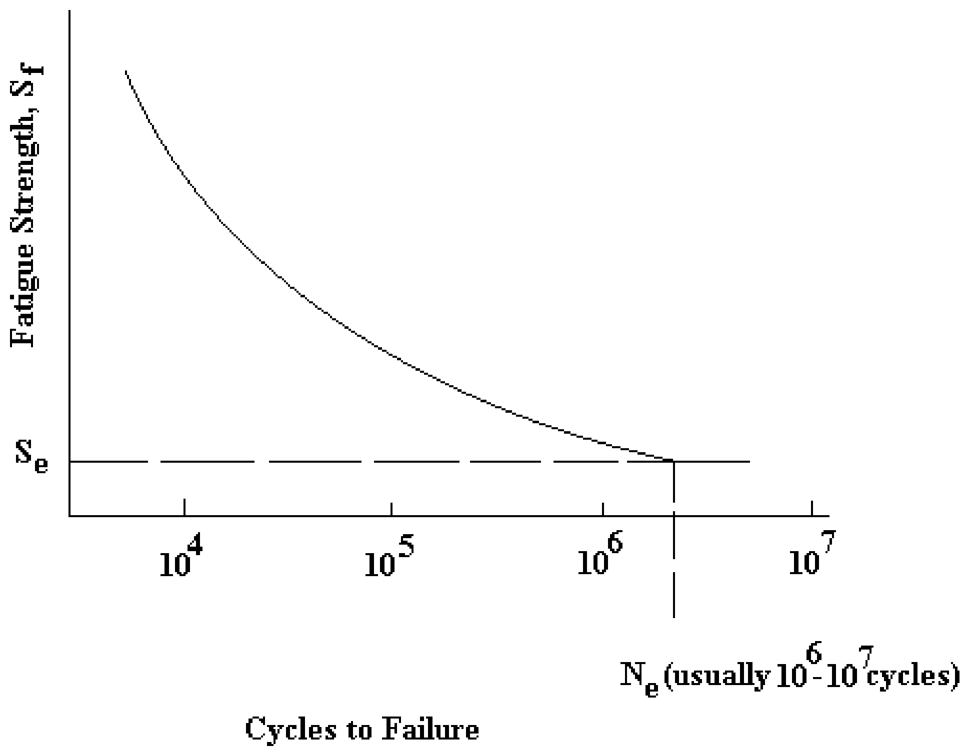

Figure C - 2. Fatigue Curve.

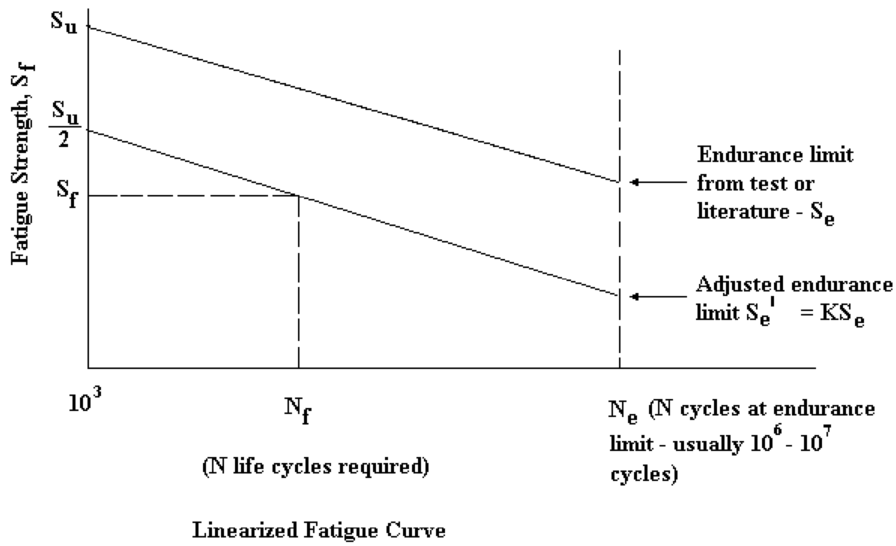

Figure C - 3. Linearized Fatigue Curve.

C.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:

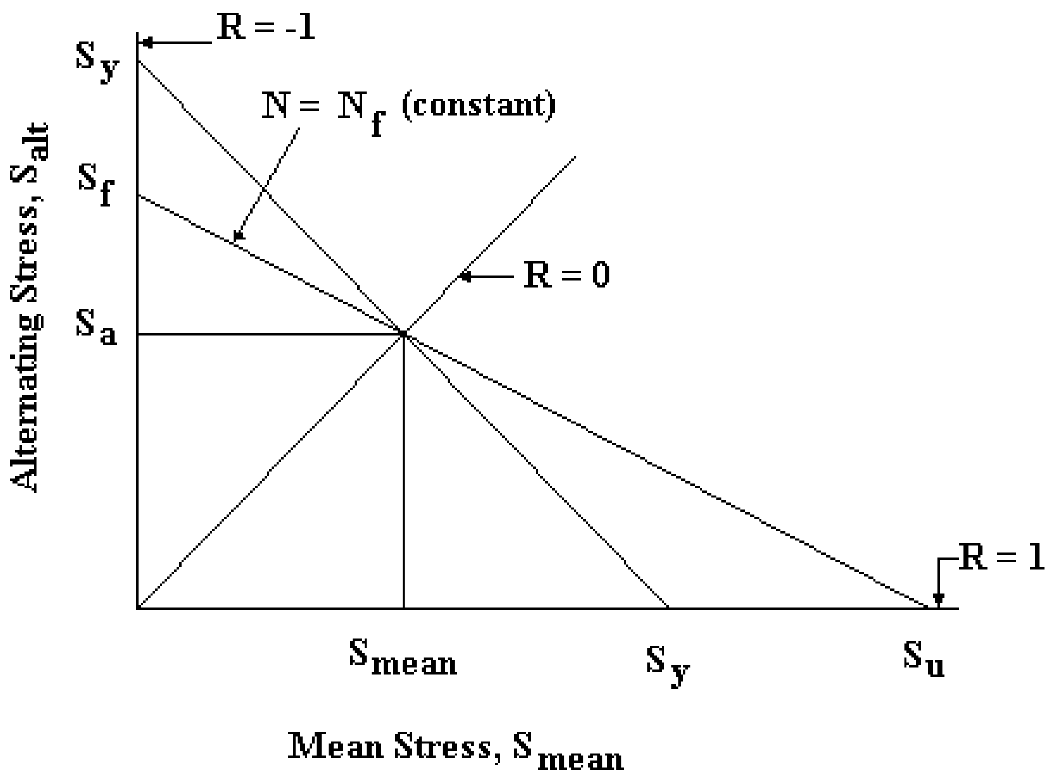

Figure C - 4. Effects of Mean Stress.

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

<u>Case 2</u>

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 2.14.2.

APPENDIX D. FRACTURE MECHANICS ANALYSIS

D.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 ΔK) 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 shall 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 shall be avoided (e.g., critically stressed parts where failure may cause injury or destroy expensive equipment). Less rigorous life-management methods (see Appendix C) 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 that 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 2.14.2.

b. Required Data: To perform a fracture mechanics analysis, it is necessary to have fatigue crack growth and fracture data set at operating conditions, as well as 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) ΔK_{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 2.3.5.

(c) For Steel Alloys Only, Charpy V-Notch data may be used per Appendix D.1.

(d) If (a)-(c) are not feasible, the manufacturer shall 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 D - 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 shall 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.

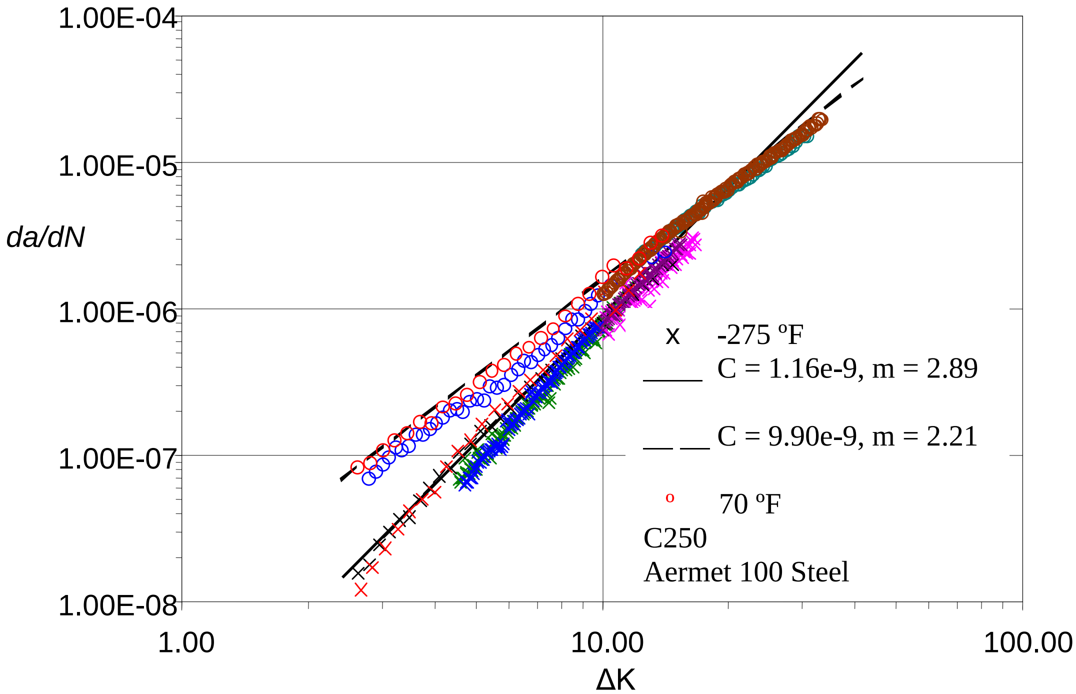

Figure D - 1. Fatigue crack growth data (da/dN vs. ΔK) and curve fits for two steels at 70ºF and –275ºF.

(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 D - 2.

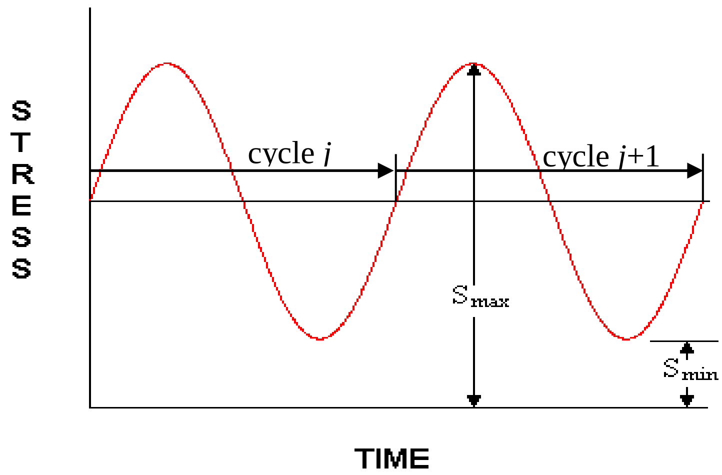

Figure D - 2. Schematic of cyclic stresses.

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

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

NDE 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. ΔK), fracture toughness data (K_{Ic}), and knowledge of the nondestructive evalution methods (NDE) 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 NDE crack size. Sample flaw sizes are given in Table D - *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, ΔK, is used such that

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

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 D - 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,

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

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

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

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

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

To complete the fracture analysis, an inspection interval shall be established. In the fracture analysis prescribed herein, there shall 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

$$\text{Inspection interval} = \frac{N_{tot}}{8} \quad (9)$$

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

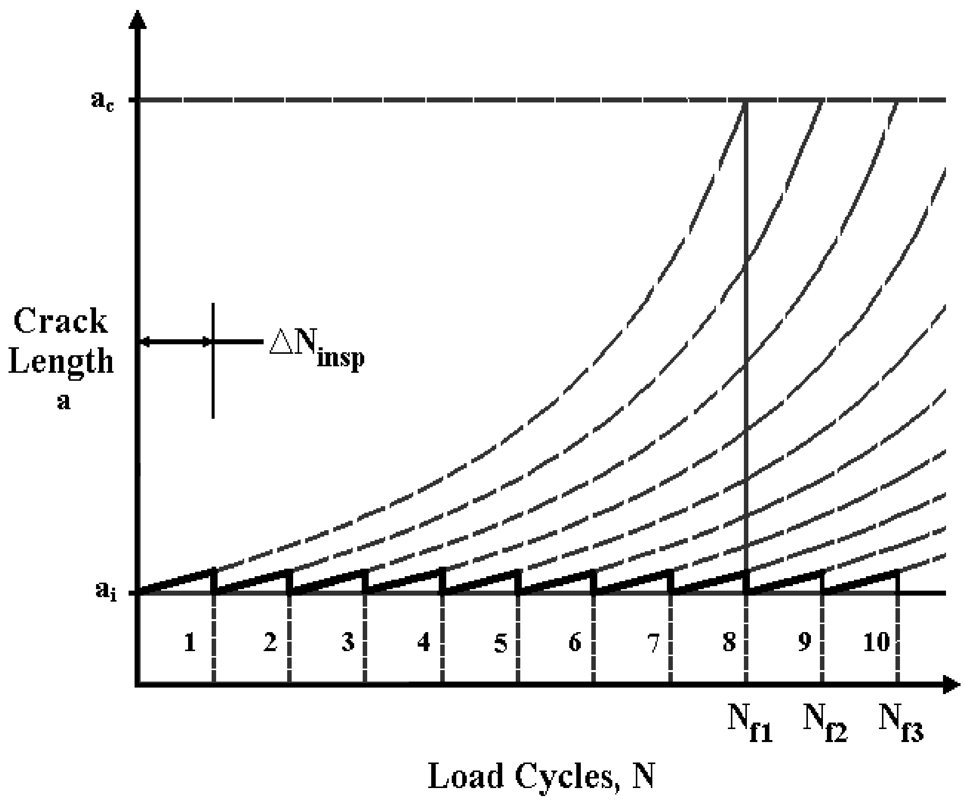

Figure D - 3. Schematic illustrating damage-tolerance fatigue-life management.

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 shall be at least four times the NDE initial crack size

$$a_c \geq 4a_1 \qquad (10)$$

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

$$\text{Inspection interval} = \frac{N_{tot}}{8} \qquad (11)$$

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 D - 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} shall not exceed 1.2 times K_{Ic}, where K_{Ie} is defined as

$$K_{Ie} = K_{Ic}\left(1 + \frac{K_{Ic}}{S_y}\right) \text{ and } K_{Ie} \leq 1.2K_{Ic} \qquad (12)$$

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 shall 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, ΔK_{th}, defines a combination of stress level and crack length where cracks do not propagate, *i.e.* any loading below ΔK_{th} produces no damage. For a variety of steel, aluminum, and titanium alloys, a conservative estimate of threshold is defined as

$$\Delta K_{th} = 0.0001UE \qquad (13)$$

where U is defined in equation (2) and E is the elastic modulus. To utilize the threshold, evaluate equation (10) such that if $$U\left(S_{j_{max}} - S_{j_{min}}\right)\sqrt{\pi a_j} \le \Delta K_{th} \text{ then } da_j = 0 \tag{14}$$

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. ΔK, K_{Ic}, K_{Ie} and ΔK_{th}) shall meet the integrity requirements outlined in B.1b.

(2) The geometry shall be representative of the component under investigation.

(3) The initial NDE 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 D - 1, and the shape of the crack is to be an aspect ratio (*a/c*) of 1.

The fatigue crack growth analysis shall 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) shall be met. If the analysis cannot meet these requirements a reassessment of the loads, component geometry and/or material may be required.

D.2 EXAMPLE OF LIFE CALCULATION

Assume a part for cryogenic operation (–275^o 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^{o}F are expressed as:

$C = 1.16 \times 10^{-9}$, $m = 2.89$, $K_{Ic} = 65$ 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

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

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

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

$$0.374 = 0.100 + \sum_{j=1}^{N} da_j = 0.100 + \sum_{j=1}^{N} 1.16x10^{-9}\left(0.806(60-10)\sqrt{\pi a_j}\right)^{2.89}$$

For the first cycle, j=1

$$da_1 = 1.16x10^{-9}\left(0.806(60-10)\sqrt{\pi 0.100}\right)^{2.89} = 1.20x10^{-5}\text{in}$$

For the second cycle, j=2

$$da_2 = 1.16x10^{-9}\left(0.806(60-10)\sqrt{\pi 0.100}\right)^{2.89} = 1.20x10^{-5}\text{in}$$

For the third cycle, j=3

$$da_3 = 1.16x10^{-9}\left(0.806(60-10)\sqrt{\pi 0.100}\right)^{2.89} = 1.20x10^{-5}\text{in}$$

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 shall be at least four times the NDE crack size and the inspection intervals and total life, with a safety factor of two, shall 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 NDE crack size of 0.100 inches.

The design fails the critical crack size requirement as prescribed in Section D.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^{½}.

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.

To meet the two criteria for fatigue life in Section B.1d, the critical crack size shall be at least four times the NDE crack size and the inspection intervals and total life, with a safety factor of two, shall 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 NDE crack size of 0.100 inches.

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

D.3 CHARPY V-NOTCH RELATION FOR STEEL ALLOYS

In cases where K_{1c} data is not available, an empirical relation exists for ferritic and martensitic steels[1] which relates plane strain fracture toughness to Charpy impact energy (see Barson, J. M.; and Rolfe, S. T.: <u>Correlation Between K_{1c} and Charpy V-Notch Test Results in the Transition Temperature Range</u>: 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 shall include two independent sources of data and be from a reputable resource such as those defined in Section 2.3f.

1) *Ref NASA Tech Memo 85816, pg 2: "This relationship, while questionable for high-toughness austenitic steels, appears to give good correlation for ferritic and martensitic steels."*

APPENDIX E. STRESS REPORT FORMAT

The Model Stress Report is meant not only to show that the model is safe to test under the predicted loads, but also to be a tool for the TE to use during the testing if circumstances arise where loads are higher than predicted, or if the research engineer wishes to expand the testing envelope. To permit this, the report needs to be complete, succinct, and well organized to permit finding the pertinent information easily and clearly. The format presented here has been shown to fulfill those requirements. Other formats that present the same information in a differently organized way may be used.

The analysis has four major sections: the introduction, reference material, loads, and the stress analysis. Additional sections may be added for specialized analyses such as divergence and fracture analyses. Appendices can be used to hold supporting documentation for such things as Finite Element Modeling, or reference documents that are needed for clarity. This could be book-sized drawings, previous analyses, supporting analyses, or other items as required.

Table of contents – A Table of Contents is included to permit the user to readily find the desired information. Not every sub-heading need be included, but sufficient detail should be included to provide direction to particular information.

Table of revisions – If the publication is a revision, state the reason for the revision and the sections being revised.

Section 1, Introduction – This section includes a brief description of the model including such things as: major model segments (wings, empennage, adjustable flaps etc), materials used (aluminum, stainless steel, fiberglass/ epoxy), overall dimensions, and weight, if significant. It also includes a statement of the type of test (flutter, pressure, force and moment), testing location(s), and test condition range. If possible, an illustration serves well to orient the reviewer with the nomenclature used for the model segments, as well as presenting an easily understood overview of the model.

The other information to be included in the introduction is the type of analysis being presented (handbook vs FEA), safety factors used for designed (Method 1, 1A, 2), a statement of top-level assumptions (in any), and a very brief conclusion (i.e. “The model meets the requirements of …”)

Section 1.1 – Summary of Critically loaded Components – This section is a table of components and the failure mode and the safety factors with respect to that mode, along with the pertinent section number. Not all of the factors need be included. Customarily, anything with safety factors less than ten are included. If desired, a full list of safety factors may be included as an appendix. Section numbers are used because page numbers can change as additions or changes are made, while section numbers usually do not change.

Section 1.2 – Reference Drawing List – This is a list of all drawings that may be needed to support the analysis or the review of such. As a minimum, it includes the model drawings, but can also include drawings of interface hardware such as stings and balances.

Section 2 - Reference Data – This section includes all relevant reference data, with source information, that is needed to support the analysis.

Section 2.1 – Material Specifications – This is a listing of the material types used, along with their heat treat condition if applicable, properties as used, and sources of the data.

Section 2.2 – Fastener Specifications – Most often this is a list of the fasteners and their properties straight out of the manufacturer's catalog (such as HOLO-KROME or Unbrako) listing the sizes, types (socket head vs flat head), strengths, and manufacturer's recommended tightening torques.

For the purposes of the report, the term fasteners include screws, bolts, nuts, pins and off-the-shelf keys. Key stock and threaded rod that is made to fit is included in Section 2.1

Section 2.3 – Equations – This section includes the equations used in the analysis with a definition of terms and the source information. Also included are specialized charts such as those for stress concentration factors, along with the necessary definition of terms and source information.

Section 3 – Loading Analysis – This section lists the loads to be used in the analysis, and their source. As a minimum, the test conditions and the coefficients to be used for analysis are defined here.

Section 3.1, 3.2, …3.n – These sections are used to calculate the loads being applied to the major components. These load calculations usually are broken down to the component level (such as to a flap). These loads are the starting point for the stress calculations that occur in Section 4. Distribution of these loads to brackets and fasteners is included in Section 4 with the analysis because the distribution of the load is usually a variable with the design. As the design develops and changes as required, the loads in this section do not change, while the load distribution to a particular bracket or screw may.

These sections includes a brief description of the part, its relationship to its neighbors, and the loading. Diagrams of the parts such as free-body diagrams can be included as required for clarity.

Equations are listed in the first step prior to substitution of values. The values are then substituted and the result listed. If the analysis is suited for tabular presentation (such as with Excel), then the first calculation is presented completely, followed by the table with the sample calculation, as well as any other relevant results.

Section 4 – Stress Analysis – This section includes the actual stress calculations for the components and their fasteners.

Section 4.1, 4.2, …4.n – The analysis of the parts is divided into logical segments, such as bending, shear, screw loading, pin loading, etc. A brief description of the loading on the part and the source in Section 3 where the load values utilized originate is required. A free-body-diagram along with three view or isometric view layouts go a long way to increase the clarity of the analysis as well as serving as a snapshot for the analyst to assure that all loading is included and the answers make sense.

Subheadings are utilized in the organization of the analysis to permit easy discussion of particular items via phone or e-mail. As an example, a section may be titled "Outboard

Flap Bracket." Subheadings would be used for the analysis of the bracket itself in shear and bending, and then for the flap to bracket fasteners, and then the bracket to spar fasteners.

Equations are listed in the first step prior to substitution of values. The values are then substituted and the result listed. If the analysis is suited for tabular presentation (such as with Excel), then the first calculation is presented completely, followed by the table with the sample calculation and the balance of the calculations.

The material type and applicable strength allowables are then listed and the calculation of safety factors is performed. For threaded fasteners, the tightening torque used (either calculated or manufacturer's recommended) and the resulting preload is then computed.

When Finite Element Analysis (FEA) is utilized in the analysis of the parts, a discussion of the model is presented as well as its constraints, loading, and results. Also, verification of the results and model convergence need to be included.

Section 5 – Other Analyses – This section is typically used for calculations such as divergence, fracture, and fatigue. Any other supplementary analyses can be included as applicable.

As with the preceding sections, sufficient information is presented to frame the problem, show the analysis, and list results and any discussion that may be required.

Appendices – Appendices may be added as required to include reference information such as material test results, previous analyses performed, etc. Essentially, any information that needs to be available for reference or is pertinent to the model but is not a part of the current calculations may be included in an appendix.