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WIND TUNNEL MODEL SYSTEMS CRITERIA

DOCUMENT HISTORY LOG

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FOREWORD

This NASA Technical Standard provides uniform engineering and technical requirements for processes, procedures, practices, and methods that have been endorsed as standard for NASA programs and projects, including requirements for selection, application, and design criteria of an item.

This standard establishes the mandatory requirements for model systems to be tested in specified wind tunnels, and may be made mandatory (wholly or in part) for model systems in other facilities by invocation by the appropriate facility personnel.

Requests for information, corrections, or additions to this standard should be submitted to the OSMA by email to Agency-SMA-Policy-Feedback@mail.nasa.gov or via the "Email Feedback" link at https://standards.nasa.gov.

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Approval Date

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WIND TUNNEL MODEL SYSTEMS CRITERIA

1. SCOPE

1.1 Purpose

1.1.1 The purpose of this NASA Technical Standard is to set forth criteria for the design, analysis, quality assurance, and documentation of wind tunnel model systems to be tested at various NASA facilities. It is intended to ease the transition of testing of a model system from one facility to another among the centers.

1.1.2 The criteria contained in this standard are intended to prevent model system failure and facility damage.

1.1.3 The requirements in this standard are required and shall be made mandatory by applicable contract for model systems to be tested in the facilties listed in 1.2.1 and may become mandatory (wholly or in part) for model systems in other facilities, as established by each Center's governing board.

1.2 Applicability

1.2.1 This standard is applicable to all civil servants, contractor, and outside producers of model systems. This standard is required for systems to be tested at the following NASA facilities:

a. LaRC Transonic Dynamics Tunnel.

b. LaRC 14- by 22-Foot Subsonic Tunnel.

c. LaRC National Transonic Facility.

d. LaRC 0.3-Meter Transonic Cryogenic Tunnel.

e. LaRC 20-Inch Supersonic Wind Tunnel.

f. LaRC Unitary Wind Tunnel.

g. LaRC 8-Foot High-Temperature Tunnel.

h. GRC 10- by 10-Foot Supersonic Wind Tunnel.

i. GRC 8- by 6-Foot Supersonic Wind Tunnel.

j. GRC 9- by 15-Foot Low-Speed Wind Tunnel.

k. GRC Icing Research Tunnel.

l. ARC 11 Foot Transonic Wind Tunnel.

m. ARC 9 x 7 Foot Supersonic Wind Tunnel.

1.2.2 This standard is approved for use by NASA Headquarters and NASA Centers and Facilities and may be cited in contract, program, and other Agency documents as a technical requirement. It may also apply to the Jet Propulsion Laboratory and other contractors only to the extent specified or referenced in applicable contracts.

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

1.2.4 Any request for relief from the safety requirements of this NASA-STD shall be done in accordance with NPR 8715.1, section "3.2 Request for Relief from Agency Institutional Safety Requirements"

1.3 Implementation

1.3.1 Implementation of this process is the responsibility of the particular facility's designated representative (DR) who has the authority to implement the criteria in this process. {i.e. Facility Safety Head (FSH) @ Langley Research Center (LaRC), Lead Test Engineer (LTE) @ Ames Research Center (ARC) and Glenn Research Center (GRC)}. The DR may be assisted by a Model Systems Engineer (MSE).

1.3.2 The lead test representative {i.e. LTE, Technical Project Engineer (TPE), Research Project Engineer (RPE), or Test Engineer (TE)} has the responsibility of ensuring that the model system design meets the criteria of this standard.

1.3.3 Any deviations from or exceptions to these criteria shall be addressed according to the deviation procedure given in Section 8.

1.3.4 For previously tested model systems, the MSE or DR shall review any modifications that affect the safety of the model. *This requirement applies to a model being tested in a facility as described in Section 1.2.*

1.3.5 The DR shall determine the need for the review of the analysis of a previously tested model system.

1.4 Design and Fabrication 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 may suffice for most 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 shall be held for those designs that are especially complicated, potentially hazardous to NASA facilities, or require a number of deviations as defined in section 8. The DR is the cognizant person for implementing these reviews, In addition, the FSH, TPE, RPE, TE, or MSE can request a formal engineering review.

1.4.4 Relief to institutional safety requirements require evaluation from the Center Institutional Safety Discipline Leads (Pressure Systems Managers (PSM), Authority Having Jurisdiction (AHJ) for Fire Protection and Life Safety, Explosives Safety Officer (ESO), Safety Manager, Lifting Devices and Equipment Manager (LDEM), Fall Protection Program Administrator (FPPA), and Center Range Flight Safety Lead (CRFSL)) and approval from the Center Institutional Safety Authority as appropriate.

1.5 Additional Requirements

1.5.1 The DR shall have the unilateral authority to impose additional requirements beyond those specified in this standard when they determine such requirements are necessary to ensure personnel or facility safety.

1.5.2 These requirements may include mitigation strategies and/or testing to prove assumptions or as qualifiers.

2. APPLICABLE AND REFERENCE DOCUMENTS

2.1 Applicable Documents

The documents listed in this section contain provisions that constitute requirements of this standard as cited in the text. Use of more recent issues of cited documents may be authorized by the responsible Center Institutional Safety Discipline Lead. The applicable documents are accessible via the NASA Technical Standards System at https://standards.nasa.gov or may be obtained directly from the Standards Developing Organizations or other document distributors.The documents listed in this section contain provisions that constitute requirements of this NASA Technical Standard to the extent cited herein.

2.1.1 Government Documents

DOD/NASA ACDG	Advanced Composites Design Guide, Air Force Wright Aeronautical Laboratories, Dayton, OH, prepared by Rockwell International Corporation, 1983
ASMD	Aerospace Structural Metals Database (ASMD)
MMPDS	Metallic Materials Properties Development and Standardization Handbook
NPR 7120.8	NASA Research and Technology Program and Project Management Requirements
NPR 8715.1	NASA Safety and Health Programs
NASA-STD-8719.17	NASA Requirements for Ground-Based Pressure Vessels and Pressurized Systems (PVS)
SAE R-422	Composite Materials Handbook

2.1.2 Non-Government Documents

ASTM E399	Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness of Metallic Materials
ASTM E647	Standard Test Method for Measurement of Fatigue Crack Growth Rates
ASTM SNT-TC-1A	Personnel Qualification and Certification in Nondestructive Testing

2.2 Reference Documents

The documents listed in this section do not constitute requirements of this standard, but are cited in the text to provide further clarification and guidance.

2.2.1 Government Documents

AFML-TDR-64-280	Cryogenic Materials Data Handbook, Volumes I and II. Technical Documentary Report
AIAA-2001-0757	Cryogenic Model Materials
A027-9391-XB2	Test Planning Guide for High Speed Wind Tunnels"
APR 8715.1C10	Ames Research Center Pressure System Safety
ASME B31.3	Process Piping Code
ASME/BPVC SEC II-D	Boiler and Pressure Vessel Code
GLP-QS-8715.1	Glenn Research Center Safety Manual
GLP-QS-8715.1.7	Glenn Research Center Pressure System Safety
LAPD 4520.1	Langley Research Center (LaRC) Requirements for Safety-Critical Product Testing
LAPD 5330.3	Langley Research Center (LaRC) Standards for the Acquisition of Threaded Fasteners (Bolts)
LMS-CP-4505	Purchase Requisition (PR) Initiation/Modification/Cancellation and Supporting Documentation
LPR 1710.40	Langley Research Center Pressure Systems Handbook
LPR 1740.4	Facility System Safety Analysis and Configuration Management
MCIC-HB-04	Handbook on Materials for Superconducting Machinery. Metals and Ceramics Information Agency Report
NASA CR 172620	Materials and Techniques for Model Construction
NASA/TM 84625	Fabrication Division Ultrasonic Inspection Specification for Critically Stressed Components
NASA TM 85805	Fastener Load Tests and Retention Systems for Cryogenic Wind Tunnel Models
NASA-TM-85816 (1984)	Grain-Refining Heat Treatments to Improve Cryogenic Toughness of High-Strength Steels, p. 2

NASA/TM—105771	NASA Lewis 8- by 6- Foot Supersonic Wind Tunnel User Manual
NASA/TM—106247	NASA Lewis 9- by 15- Foot Low-Speed Wind Tunnel User Manual
NASA/TM—1999-208478/REV1	NASA Glenn 1– by 1–Foot Supersonic Wind Tunnel User Manual
NASA/TM—2003-212004	NASA Glenn Icing Research Tunnel User Manual
NASA/TM—2004-212697	User Manual for NASA Glenn 10- by 10-Foot Supersonic Wind Tunnel
NBSIR 79-1624	Materials for Cryogenic Wind Tunnel Testing. National Bureau of Standards Report

2.2.2 Non-Government Documents

Barsom, J. M.; Rolfe, S. T. (1970)	Correlation Between KIc and Charpy V-Notch Test Results in the Transition Temperature Range. ASTM, STP466,Impact Testing of Metals, pp. 281-302
Machinery's Handbook	Machinery's Handbook

2.3 Order of Precedence

2.3.1 Where conflicts exist between this standard and applicable Federal and State regulations, the applicable regulations take precedence.

2.3.2 Where conflicts exist between this standard and applicable Agency directives, the applicable Agency directives take precedence.

2.3.3 Where conflicts exist between this standard and standards that contain provisions that constitute requirements of this standard as cited in the text, this standard takes precedence, except in the case where those standards are applicable to Federal or State regulations.

2.3.4 Where conflicts exist between a requirement that is meant to be applied generally across all technical disciplines and a requirement that is applicable to a specific technical discipline, the requirement that is applicable to a specific technical discipline takes precedence.

2.3.5 Interpretation and clarification of safety requirements and further resolution of conflicts shall be resolved by the responsible Institutional Safety Discipline Lead.

3. ACRONYMS AND DEFINITIONS

3.1 Acronyms and Abbreviations

AHJ	Authority Having Jurisdiction
AISC	American Institute of Steel Construction
ANSI	American National Standards Institute
APR	Ames Procedural Requirements
ARC	Ames Research Center
ASME	American Society of Mechanical Engineers
ASNT	American Society for Nondestructive Testing
ASTM	ASTM International
AWS	American Welding Society
CRFSL	Center Range Flight Safety Lead
CVN	Charpy V-Notch
DR	Designated Representative
DT	Damage Tolerance
ESO	Explosives Safety Officer
FEA	Finite Element Analysis
FME	Force Measurement Engineer
FPPA	Fall Protection Program Administrator
FSH	Facility Safety Head
GLM	Glenn Library Manual
GRC	Glenn Research Center
LAPD	Langley Policy Directive
LaRC	Langley Research Center
LDEM	Lifting Devices and Equipment Manager

LPR	Langley Procedural Requirements
LTE	Lead Test Engineer
MSE	Model Systems Engineer
NCS	NASA Communication Services
NDT	Nondestructive Testing
PQR	Procedure Qualification Records
PR	Purchase Requisition
PSM	Pressure Systems Manager
PVS	Pressure Vessels and Pressurized Systems
RAC	Risk Assessment Code
RPE	Research Project Engineer
QAS	Quality Assurance Specialist
QS	Quality System
SDS	Safety Data Sheet
TE	Test Engineer
TM	Technical Memorandum
TPE	Technical Project Engineer
WPQ	Welder Performance Qualifications
WPS	Weld Procedure Specifications

3.2 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 $2,000,000 (Type A or B Mishap).

Critical. A failure that may cause lost time injury or illness, and/or system/equipment damage between $500,000 and $2,000,000 (Type C Mishap).

Resonant (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 4.4.2) analysis. For nonmetals, the TPE, MSE, TE, or DR 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.

Force Measurement Engineer. 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).

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

Mandatory NASA facility. A wind tunnel facility that is to abide by the criteria established by this document.

Model systems. Model systems covered by this NASA Technical Standard are defined as models, flow survey devices, splitter plates, model support hardware including force balances (Section 4.13 only), and stings. The term model system does not include the following:

a. Model support equipment that is a permanent part of the facility.

b. Off-the-shelf components, such as gearboxes, motors, actuators, instrumentation mounts, and so forth, which are not critical to the structural integrity of the model system and whose failure cannot result in facility damage.

c. Ancillary equipment, such as arc sectors, cables, brakes, and foundations that are not a part of the model itself.

Model Systems 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 DR in interpreting the requirements for compliance with this NASA Technical Standard.

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 NASA Technical Standard.

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.

Pressure Systems Manager (PSM). The person at a NASA Installation designated by the Installation Director as the Institutional Safety Discipline Lead having technical oversight for ground-based pressure systems, managing safety policies and programs for pressure systems and ensuring their implementation at the NASA Installation. The PSM serves as the jurisdiction having authority for PVs for facilities operating under exclusive Federal jurisdiction and is analogous to a state chief boiler inspector in regards to the issuance of operating permits. However, neither the PSM nor their staff functions as a National Board inspector unless they are so certified by the National Board of Boiler and Pressure Vessel Inspectors.

Quality Assurance Specialist. A specialist assigned to support the implementation of the quality assurance requirements.

Research Project Engineer. The research organization cognizant engineer assigned the responsibility for configuration definition and testing of the model system. The RPE is to coordinate activities with the TE.

Test Engineer. The resident engineer at the test facility in which the test under consideration will be performed.

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

Tunnel Flow Start-up. A transient loading condition proceding downstream due to the above sonic flow initiation in the tunnel.

Tunnel Flow Breakdown. A transient loading condition proceding upstream due to the loss of above sonic flow in the tunnel.

Unstart Condition. Relative to a body or wing - The flow past the body on one side or in one area drops below sonic conditions while the remainder maintains above sonic conditions. This condition causes a force im-balance as the unstarted flow static pressure is above the full flow static pressure.

Relative to an inlet – The flow inside the inlet drops below sonic conditions while the flow past the inlet remains supersonic.

4. DESIGN AND ANALYSIS

4.1 General

4.1.1 Design Load

4.1.1.1 The design loads data shall be established by the appropriate personnel and be consistent with safe operating limits of the facility, and agreed to by the facility DR. The loads may come from a combination of sources, but should be agreed to by all parties involved. Along with the running loads, spurious loading conditions (e.g., start-up, unstart, and flow breakdown loading particular to the facility) must be considered.

4.1.1.2 Dimensional tolerances, potential model installation errors, and potential local flow conditions create mis-alignments that shall be considered when determining loads on model components.

4.1.1.3 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.

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

4.1.1.5 The design loads data shall be a part of the Model Systems Report (see Section 7).

4.1.1.6 The documentation shall include, the following:

a. Aerodynamic and thermal loads for the extremes of the test conditions seen for the various model configurations.

b. Design cycle life requirements (if applicable).

c. Inertia driving forces (if applicable).

d. Frequencies for dynamic and transient testing (if applicable).

e. Facility-specific starting, stopping, and un-start loads (if applicable). Consult the facility DR for specific values for the test conditions planned.

4.1.2 Critically Loaded/Stressed Components

4.1.2.1 A list of all critically loaded/stressed components, including fasteners, shall be generated and included in the Model Systems Report.

4.1.2.2 The worst-case impact on the facility if component failure occurs shall be identified for each critically loaded/stressed 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?

4.1.2.3 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.

4.2 Model/Test Hardware Material Selection

4.2.1 Standards

4.2.1.1 Materials and fasteners 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.

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

4.2.2 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.

4.2.3 Verification

4.2.3.1 Materials used for critically stressed components or those materials subject to nonstandard or special processing shall have as-built properties verified at the expected test temperature whether elevated or depressed.

4.2.3.2 In particular, for cryogenic applications or applications where operating temperatures are less than the ductile-to-brittle transition temperature for a given material used, tensile and fracture toughness tests shall be performed to measure strength and toughness against expected values.

4.2.4 Galling and Galvanic Corrosion

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

4.2.4.2 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.

4.2.4.3 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 compatibility of mating materials (difference in anodic index). Use of passivation for stainless steels or coating applications for other materials is recommended. For harsh environments, cathodic protection may be required.

4.2.5 Fracture Toughness

4.2.5.1 For all models susceptible to brittle fracture (i.e. cryogenic models) and for other applications requiring high material toughness, the plane-strain fracture toughness (KIc) properties set forth in this section are mandatory for critically stressed components.

4.2.5.2 The plane-strain fracture toughness properties for all fracture critical model materials shall be greater than the toughness values used in the fracture mechanics analysis performed according to Section 4.3.4.

4.2.5.3 Acceptable documentation shall include KIc test data on the material obtained by the manufacturer using ASTM E399, Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness KIc of Metallic Materials.

4.2.5.4 If the manufacturer does not have test data available, conservative published test data available in the literature may be used if the heat treat, material chemistry, tensile strength, yield strength, and test temperature are similar to the operating condition. This literature data shall include two independent sources of data and come from a reputable resource, such as those defined in Section 4.2.6.1.

4.2.6 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, filled epoxies, and so forth.

Note: While cryogenics is classically thought of as below -150°C (-238°F), for the purposes of this standard, it is considered to be below -46°C (-50°F). Consult the facility DR for further guidance.

4.2.6.2 Cryogenic Materials Data Sources

4.2.6.2.1 Suggested sources of information on materials that have been characterized and evaluated for cryogenic uses are as follows:

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

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

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

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

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

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

g. ASME Boiler and Pressure Vessel Code ASME/BPVC SEC II-D - SECTION II-D PROPERTIES

h. ASME B31.3 Process Piping Code

4.3 Structural Analysis

4.3.1 Fatigue Analysis

4.3.1.1 The provisions of this section apply to components that are subjected to cyclic loadings to the extent that fatigue is a credible failure mode.

4.3.1.2 The fatigue analysis shall be performed on the premise that no flaws or cracks initially exist in the structure.

4.3.1.3 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 A is provided as a guide for performing fatigue design analysis and for determining the allowable oscillating stress based on model system design life requirements.

4.3.2 Fracture Analysis

4.3.2.1 A fracture mechanics analysis shall be mandatory for critically stressed components, components susceptible to brittle fracture, applications where operating temperatures are less than the ductile-to-brittle transition temperature for a given material used and all cryogenic model system components .

4.3.2.2 The fracture analysis precludes the fatigue analysis as the basis for design life calculations for components susceptible to brittle fracture, applications where operating temperatures are less than the ductile-to-brittle transition temperature for a given material used and cryogenic model systems. Details regarding performing a fracture analysis are provided in Appendix B. Three levels of analysis are presented in Appendix B, which will satisfy the fracture analysis criteria as described in this document.

4.3.3 Stress Analysis

A stress analysis shall be provided as a part of the Model Systems Report (see Section 7.1). It is to be complete and sufficiently comprehensive to require no further explanation. While many formats will suffice, a discussion of a suggested format for a stress report that meets all requirements that follow is given in Appendix C.

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

b. Each detailed analysis section shall do the following:

(1) Identify load paths.

(2) Contain a sketch showing forces and moments acting on the part (free body diagram).

(3) Include statements of the following:

(a) Assumptions.

(b) Approximations.

(c) Section and physical properties.

(d) Type and heat treat condition of the material.

(e) 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 (FEA) methods are used for model systems analysis, the documentation shall include the following:

(1) Computer-generated plots of the finite element models.

(2) Tabular or graphical summary of stress data.

(3) Detailed information on how the finite element models were verified/validated.

f. Validation of finite element models shall be by the following:

(1) Closed form solutions.

(2) Equilibrium checks.

(3) Boundary condition checks, and.

(4) Convergence accuracy of solutions.

4.3.3.1 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.

4.3.3.2 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.

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

4.3.3.4 Mesh refinement in high-stress areas shall be done to less than 5 percent mesh-to-mesh variation.

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

4.3.3.6 High stresses around point loads and constraints can sometimes be neglected if it can be shown that they are modeling-induced stresses. Typically, point constraints are used to determine reaction loads, such as in bolts, and not the actual stress at the constraint. The reaction loads are then used in closed-form analysis of the bolts.

4.3.4 Thermal Analysis

Sufficient analysis shall be performed to examine thermal stresses and distortions for steady state and transient conditions.

4.3.5 Design Life

4.3.5.1 The RPE/TE shall specify the design life requirements for the fatigue and/or fracture analysis for model system components. (See Section 4.8.3.8 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: The primary design life-cycle requirement used for analysis shall be developed by estimating 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.

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.

4.3.6 Mechanical Connections

4.3.6.1 Structural Joints

4.3.6.1.1 Welded and Brazed Joints

4.3.6.1.1.1 All welded or brazed joints not associated with pressurized systems shall be designed and fabricated in compliance with American Welding Society (AWS), American Society of Mechanical Engineers (ASME), or American Institute of Steel Construction (AISC) standards.

4.3.6.1.1.2 All welded or brazed joints associated with pressurized systems shall be designed and fabricated in compliance with ASME BPVC Section VIII, ASME B31.3 or other as appropriate standards as agreed to by the DR and PSM.

4.3.6.1.1.3 All Weld Procedure Specifications (WPS), Procedure Qualification Records (PQR) and Welder Performance Qualifications (WPQ) shall be in accordance with the applicable code of construction. Welding shall only be performed by welders qualified and current in accordance with the most applicable construction code, on such weld procedures. Both the joint and the structure near the joint are subject to the stress criteria set forth in Section 4.4, with appropriate adjustment for the effects of the process (e.g., strength reduction in the heat-affected areas).

4.3.6.2 Bolted Joints

4.3.6.2.1 PVS bolt design requirements shall be in accordance with ASME B31.3, ASME BPVC VIII-Div or other acceptable criteria agreed to by the DR and, if appropriate, the PSM. All other model bolted joint design shall satisfy the allowable stress criteria as set forth in Section 4.4 and may require independent evaluations of the strength of the joining components, particularly if dissimilar materials are involved. These evaluations may include thread shear/ tear-out, material crushing under the head, flange bending, and other item specific designs

4.3.6.2.2 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.

4.3.6.3 Bonded Joints

4.3.6.3.1 Bonded joints in metallic assemblies shall be used only when absolutely necessary due to joint configuration and loading.

4.3.6.3.2 Bonded joints shall satisfy the allowable stress criteria as set forth in Section 4.4.

4.3.6.3.3 Structural applications of bonded joints shall utilize a written procedure that specifies the steps for surface treatment, cleaning, priming (if required) and bonding, and that has been verified by test coupons.

4.3.6.4 Riveted Joints

4.3.6.4.1 Riveted joints may be utilized when necessitated due to joint configurations and material limitations (e.g., joining thin sheets of metal).

4.3.6.4.2 Riveted joints shall satisfy the allowable stress criteria as set forth in Section 4.4. Riveted joints are not permitted within pressurized vessels and systems.

4.3.7 Threaded Fasteners:

4.3.7.1 The length of thread engagement shall be sufficient to develop the required bolt strength without stripping either the internal or external threads.

4.3.7.2 A recommended method to calculate the required length of engagement can be found in the Machinery's Handbook, which considers thread geometry and the material strengths of both the fastener and the tapped hole.

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

4.3.7.4 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.

4.3.7.5 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.

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

4.3.7.7 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 4.4.3.2.

4.3.7.8 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.

4.3.7.9 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.

4.3.7.10 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.

4.3.7.11 The factor of safety for the fasteners is the appropriate load rating for the fastener, in accordance with Section 4.4.3, divided by the external load for the fastener, and shall be greater than or equal to 4 on ultimate and 3 on yield.

4.3.7.12 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.

4.3.7.13 Fasteners of #4 size and smaller can be adversely affected by installation, torquing, and removal. These may require replacement after each use. Consult the facility DR for re-use allowances when planning spares to have on-hand for the test.

4.4 Metallic Materials Allowable Stress

4.4.1 General: The allowable stress criteria for non-PVS 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 IA are based on conventional conservative approaches, which can be employed where structural design optimization is not a factor and minimum analysis effort is needed.

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.

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. PVS material allowable stresses shall be obtained from ASME BPVC Section II, Part D and ASME B31.3.

4.4.2 Method 1:

4.4.2.1 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.

4.4.2.2 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.

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

4.4.2.4 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.

4.4.2.5 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.

4.4.3 Method 1A:

4.4.3.1 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.

4.4.3.2 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.

4.4.3.3 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 4.3.1 or 4.3.2, respectively.

4.4.4 Method 2:

4.4.4.1 This method can be used when the system cannot be designed to the allowables of Methods 1 or 1A, and the stress state in the model system structure is understood to a high level of confidence. Closed-form solutions and standard handbook calculations will, in many cases, suffice.

4.4.4.2 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.

4.4.4.3 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 4.4.3.2.

4.4.5 Stress Terminology

4.4.5.1 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.

4.4.5.2 Normal Stress: The stress normal to the plane of reference.

4.4.5.3 Shear Stress: The stress tangent to the plane of reference.

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

4.4.5.5 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).

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

4.4.5.7 Incremental Peak Stress: Incremental peak stress is defined as the increment added to the stress at a point to give the total peak stress in areas of stress concentrations. The basic characteristic of a peak stress is that it causes no noticeable distortion and is objectionable only as a possible source of a fatigue crack or a brittle fracture.

4.4.5.8 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 as follows: First, general thermal stress, associated with distortion of the structure in which it occurs; and second, local thermal stress, associated with almost complete suppression of the differential expansion/contraction and thus producing no distortions. Such stresses are to be considered only for fatigue design. Transient conditions must also be considered and can sometimes produce worse stresses.

4.4.5.9 Cyclic Stress 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

4.4.6 Calculation of Combined Principal Stress

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

4.4.6.2 The stress components in the directions are then designated σ_i, σ_j, σ_k for normal stresses and τ_{ij}, τ_{jk}, τ_{ki} for shear stresses.

4.4.6.3 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.

4.4.6.4 Translate the stress components in the (i,j,k) directions (may be rectangular, cylindrical, or spherical coordinates into principal stresses σ1, σ2, σ3. Next calculate the absolute value of the stress difference σ12, σ23, σ31 from the relations:

$$\sigma 12 = abs(\sigma 1 - \sigma 2).$$

$$\sigma 23 = abs(\sigma 2 - \sigma 3).$$

$$\sigma 31 = abs(\sigma 3 - \sigma 1).$$

Note: For a biaxial state of stress σ3 = 0.

4.4.6.5 The combined principal stress intensity S is the largest (absolute value) of σ12, σ23, σ31.

4.4.7 Combined Stress Allowables

4.4.7.1 General Primary Membrane Stress Intensity, σ_m, shall not exceed the allowable membrane stress, Sm. Sm will be the smaller of:

$$1/2\ F1*S_y \text{ or } 1/3\ S_u$$

where
S_y = minimum specified yield strength
S_u = minimum specified ultimate strength,and
F1 = (0.8)[2 - S_y/ S_u], but always <= 1.0

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

$2/3\ S_y$ or $1/3\ S_u$

4.4.7.3 Primary membrane plus primary bending stress intensity, σm + σb, shall not exceed α times Sm, that is,

$$\sigma_m + \sigma_b \leq \alpha S_m$$

α = shape factor = Z (plastic modulus)/ S (elastic modulus), ≤ 1.5 for the section in bending. α = 1.5 for rectangular sections, plate and bar.

4.4.7.4 Primary plus secondary stress, shall not exceed 2.0 times Sm,

$$\sigma_m + \sigma_b + \sigma_s \leq 2S_m$$

4.4.7.5 Primary plus secondary plus incremental peak stress intensity shall not exceed the allowable alternating stress, Sa, as established by fatigue analysis (see Section 4.3.3).

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

4.4.7.6 The allowable stresses are summarized in Table 4-1, Method 2 Hand Calculated Allowable Stresses.

Table 4-1. Method 2 Hand Calculated Allowable Stresses

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	$^1/_2\ S_y$	$^2/_3\ S_y$	$^1/_3\ S_u$	$^1/_3\ S_u$
$\sigma_m+\sigma_b$	$1.5\ S_m$	$^3/_4\ S_y$	S_y	$^1/_2\ S_u$	$^1/_2\ S_u$
$\sigma_m+\sigma_b+\sigma_s$	$2.0\ S_m$	S_y	$^4/_3\ S_y$*	$^2/_3\ S_u$	$^2/_3\ S_u$
$\sigma_m+\sigma_b+\sigma_s+\sigma_p$	S_a	…	…	…	…

* Although allowable for stress concerns, consideration is to be given to the ramifications of the initial application of this stress condition.
Note: "allowable stress limits are not applicable for models operating above the creep regime"

4.4.7.7 The second theory to be used under a Method 2 analysis is the von Mises Equivalent Stress Criteria, 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 (σx, σy, σz, τxy, τxz, τyz) 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.

4.4.7.8 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:

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

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

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

b. Single Axis Stress State: For a stress state that consists of one normal stress and a shear stress, the von Mises equivalent stress is:

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

c. Von Mises Theory Allowables The maximum allowable stress shall be as listed in the following table. Due to the higher risks associated with low safety factors, consultation with facility personnel is recommended to address these issues.

Table 4-2. Von Mises Theory Allowables for FEA

Calculated Value		**Yield Strength**	**Ultimate Strength**
σ_e for highly localized peak stress values due to stress concentrations, boundary conditions, etc *		S_y	2/3 S_u
σ_e for net section stress values	LaRC	2/3 S_y	1/2 S_u
	ARC	1/3 S_y	1/4 S_u**
	GRC	2/3 S_y	1/3 S_u

* An additional concern with highly localized stresses is the potential for crack initiation. Load monitoring is advisable and may be required if the area of concern is subjected to dynamic loads.
** ARC permits 1/3 Su with stress or load monitoring

4.4.8 Specialized Tunnel Requirements

4.4.8.1 8' High Temperature Tunnel (8' HTT) Model Requirements:

4.4.8.1.1 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 Section 8.0.

4.4.8.1.2 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.

4.4.8.1.3 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.

4.4.8.1.4 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.

4.4.8.1.5 The facility's customers shall conduct the appropriate stress analyses and submit their analyses to NASA's MSE.

4.4.8.1.6 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, the test customer, and the facility safety head.

4.4.8.2 Icing Research Tunnel (IRT) Model Requirements

4.4.8.2.1 The IRT at GRC is a specialized test facility with little chance of facility damage when model parts fail. When the allowables of this section cannot be met for the test article or its mounting hardware to be used in this facility, the hardware can still be tested by following the flight hardware requirements in section 4.11.3 Special Tests, or by utilizing the deviation procedures listed in Section 8.0.

4.4.8.2.2 The customer shall conduct a reasonable effort to accurately predict the stresses imposed on their model and its mounting hardware when subjected to the test conditions in the IRT. This is usually done in concert with facility experts.

4.4.8.2.3 It is highly desirable from all points of view that the model be capable of withstanding the 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 with existing flight hardware.

4.4.8.2.4 The customer shall conduct the appropriate stress analyses for their test article and its mounting hardware and submit their analyses to the facility's DR.

4.4.8.2.5 Ultimately, the decision to test an article with a low safety margin shall be reached jointly between the facility engineers, the test customer, and the facility DR.

4.5 Nonmetallic and Rapid Protoyping Materials Requirements

4.5.1 Composites

4.5.1.1 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.

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

4.5.1.3 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).

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

4.5.1.5 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 to show compliance with a documented failure criterion shall be required.

4.5.1.6 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.

4.5.2 Wood

4.5.2.1 The orthotropic nature of the mechanical properties of wood as well as environmental effects shall be considered when determining allowable stresses.

4.5.2.2 Allowable stresses shall be 1/3 of the minimum strength for the appropriate load type and orientation with respect to the grain.

4.5.3 Glass

Due to the brittle nature of glass, the allowable stress shall be 1/10 the material ultimate strength. Care must be taken with the edge finish to remove any micro-cracking or other defects that would present a stress riser.

4.5.4 Additively Manufactured Materials

4.5.4.1 Small, trivially stressed detail parts may be used with minimal or no analysis and testing, with concurrence of the DR.

4.5.4.2 For structural applications, material property samples shall be made alongside each build of parts, with the same representative build orientation. A “build” is considered to be one group of parts built at the same time on the platen.

4.5.4.3 When first using a new process, machine, or supplier, the samples shall be built in three build directions: flat, 45 degrees, and upright. The upright sample shall encompass the full height of the build.

4.5.4.4 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).

4.5.4.5 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 used (Section 4.4).

4.5.4.6 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 (new machine, new raw material, different machine settings), the sample requirement resets.

4.5.4.7 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).

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

4.5.4.9 Exact requirements shall be established on a case-by-case basis by the DR, along with the MSE and the test engineer.

4.5.4.10 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. Additively manufactured material or model support shall comply with NASA-STD-6033.

4.5.5 Other Materials

Other materials shall be dealt with on an individual basis with concurrence of the DR.

4.6 Stability

4.6.1 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.

4.6.2 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.

4.6.3 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.

4.6.4 Dynamics

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

4.6.5 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.

4.7 Pressurized Systems

4.7.1 General

4.7.1.1 Pressurized 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.

4.7.1.2 Pressurized systems inside the model which have the maximum pressure (in lb/in*2) times the maximum projected area (in in*2) of the pressurized surface greater than 7,000 pounds, and systems outside the model shall be designed and fabricated according to the following codes:

(1) ASME Boiler and Pressure Vessel Code Section VIII, Division 1, 2, or 3.

(2) ASME B31.3 - Process Piping Code.

(3) One of the following:

(a) LPR 1710.40, "Langley Research Center Pressure Systems Handbook"

(b) APR 8715.1C10 "Ames Research Center Pressure System Safety"

(c) GLP-QS-8715.1.7 "Glenn Research Center Pressure System Safety"

4.7.2 Relief Devices

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

4.7.2.2 Overpressure protection for PVS shall be in accordance with NASA-STD-8719.17, ASME BPVC Section XIII, Section VIII, and ASME B31.3.

4.7.2.3 If relief devices are present in the model, the effects of loads created by venting shall be considered for the model and its support system, in concert with other loading present (aero, dynamic, etc).

4.7.3 PVS Pressure Testing

4.7.3.1 PVS shall be pressure (hydrostatic or pneumatic) tested in accordance with the applicable NCS (ASME BPVC VIII Div. 1, 2, or 3 or ASME B31.3).

4.7.3.2 Hydrostatic testing of pressure systems is the preferred method of pressure testing.

4.7.3.3 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.

4.7.3.4 Pressure testing is potentially hazardous. All personnel shall be excluded from a predetermined hazard zone. Adequate safety precautions are to be taken to ensure safety of personnel and equipment with regard to test procedures.

4.7.3.5 After hydrostatic pressure testing, components shall be dried appropriately utilizing a gas that complies with the cleanliness requirements, as applicable.

4.7.3.6 A pneumatic pressure test of PVS shall be done if a hydrostatic test is not feasible.

4.7.3.7 The DR may designate a test pressure lower than 1.5 times the design pressure times the ratio of the material strength at pressure test temperature to the material strength at design temperature if warranted by design considerations and accepted in the hazard analysis.

4.7.3.8 Over pressure testing shall conform to the testing requirements set forth in LPR 1710.40, "Langley Research Center Pressure Systems Handbook", APR 8715.1C10 "Ames Research Center Pressure System Safety", or GLP-QS-8715.1.7 "Glenn Research Center Pressure System Safety".

4.8 Rotating Systems

4.8.1 General

The special requirements set forth in this Section apply to model systems that have rotating parts, such as propellers, rotors, ducted and un-ducted fans, compressors and turbines. A rotor, for this document, is defined as predominantly providing vehicle lift with aero-elastic blades, while a propeller, a ducted or an un-ducted fan, predominantly provides vehicle thrust. In situations where these definitions are unclear, the DR will determine the appropriate criteria.

4.8.2 Design for Normal Operation:

a. The customer should provide the NASA DR with rotating model system resonance points if they exist. Before a rotating model can be tested in a NASA facility, the customer must provide the DR with a Campbell diagram that shows possible resonance points (i.e., intersection points between rotating system natural frequency lines and engine order lines (straight lines of frequency as a function of component speed)). An example of a typical Campbell Diagram is as follows:

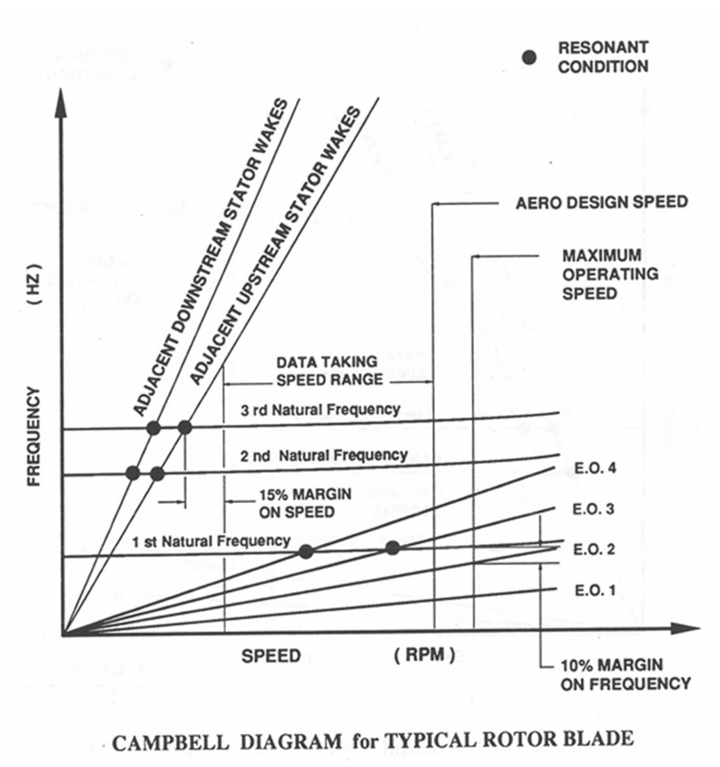

Figure 4-1. Campbell Diagram for Typical Rotor Blade

b. 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.

c. 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.

d. 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 4.8.7). When possible, this is accomplished by the use of strain gage instrumentation mounted on the model blades in order that resonance points are avoided during testing. If use of strain gages is not possible, laser light probes or similar means of sensing blade stress must be implemented.

e. Propeller model drive systems shall be designed to operate at 20 percent above the maximum test speed.

f. Compressor and turbine model systems shall be designed to operate at 15 percent above the maximum test speed.

g. Rotor model systems shall be designed to operate at 10 percent above the maximum test speed.

h. Steady-state stress in rotating components due to centrifugal loads shall be determined at the maximum operating speed (test speed + apropriate margin, 20%, 15% or 10%). This stress shall be combined with the maximum steady-state stress due to fluid forces and untwist forces. Steady-stresses shall not exceed material strength, applying appropriate safety factors, which are as follows:

Yield (0.2% offset) Safety Factor = 1.1

Ultimate Safety Factor = 1.5

Fatigue Safety Factor = 1.33

i. Fasteners, which are designed to carry loads associated with rotation, shall be secured by mechanical and/or chemical locking (see Section 4.3.7.11).

j. 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 non-rotating parts, such as a nacelle, and to the model fuselage fall into this category.*

k. Provisions shall be made for balancing the system (see Section 4.8.6).

l. Bearing loads, life and lubrication requirements shall be specified for the expected operating environments.

m. Particular models may require the consideration of periodic rotational speed loadings. These loadings may result from struts, inlet guide vanes, outlet stators, and other components.

4.8.3 Design for System Failure Event

4.8.3.1 Models shall be designed such that after an initial failure, no further failure occurrence will cause facility damage during the tunnel shutdown process, i.e., ultimate safety factors are greater than 1.0 when unbalanced loading is considered.

4.8.3.2 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.

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

4.8.3.4 Compressor and turbine model systems shall be designed such that after the loss of one blade no further failure occurrence will cause facility damage during the tunnel shutdown process.

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

4.8.3.6 For propeller, rotor, compressor, and turbine models, 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.

4.8.3.7 For propeller model high-risk applications (that is, rotating component(s) whose failure would result in model loss and/or damage to the tunnel fan), the model propeller drive system shall be designed for positive containment of drive system components, excluding the hub assembly. The DR and the customer should discuss the need of using a containment shield around the model based on the risk of the test program. Positive containment is not required for rotor models.

4.8.3.8 The model systems should be equipped with a control system that will sense an unbalanced load and/ or overspeed, then initiate an automatic shutdown of the rig.

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

4.8.3.10 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 Section 8 “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. The approving authority shall be informed of anticipated deviation requests.

4.8.4 Analysis

4.8.4.1 Natural mode shapes and frequencies of the system coupled with the model test bed shall be calculated. These calculations are intended to be used to identify potential resonance or other instabilities, which might be alleviated during the design phase. At the discretion of the DR, the critical natural modes and frequencies may be determined experimentally (see Section 4.8.5).

4.8.4.2 Dynamic stability analyses is to be required only if specified by the DR.

4.8.4.3 The provisions of Section 4.3, with the exception of Sections 4.3.5a. and 4.3.5b, shall apply to all rotating components.

4.8.4.4 All of Section 4.3 shall apply to the non-rotating components in the model.

4.8.5 Structural Testing

The RPE/TE or DR shall establish acceptance criteria based on the requirements that follow.

4.8.5.1 Propeller Blades

One blade from each manufactured set of propeller, compressor, or turbine 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 DR, 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).

Note: A waiver to this requirement can be requested for blades that have been instrumented with strain gages and numerically analyzed with a structural design code (such as finite element).

4.8.5.2 Rotor Blades

4.8.5.2.1 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 DR, the test can be made on a test specimen that simulates the critically loaded part of the blade.

4.8.5.2.2 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. The blade manufacturer should specify the acceptable variation in blade frequency response levels and notify the DR.

4.8.5.2.3 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 if analysis shows potential for dynamic excitation in operating range.

4.8.6 Balancing

4.8.6.1 The difference in weight and center-of-gravity between various blades in a given propeller, rotor, compressor, or turbine assembly shall be as small as practical and equal to or less than the value used for analysis.

4.8.6.2 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 Su 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 Su, radians per second for Ω, and in./sec2 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.

4.8.7 Demonstration Testing

4.8.7.1 Demonstration run-up testing of the model system (test configuration) shall be performed prior to tunnel entry, if possible. 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 DR.

4.8.7.2 Demonstration tests shall demonstrate safe operation over all operational speed ranges up to 20 percent above design speed for propeller systems, 10 percent over design speed for rotor systems, and 15% for compressor and turbine systems unless the DR approves a lower speed, because of aeromechanical stability considerations.

4.8.7.3 Heavily instrumented turbomachinery that undergoes thorough checkout in the facility prior to test and with appropriate safety shielding during the test are exempt from this requirement at the discretion of the facility DR.

4.8.8 Inspection

4.8.8.1 All components of the rotating system including blades, drive shaft, bearing, hub, and so forth, shall be inspected at time of manufacture and assembly and at established intervals during use.

4.8.8.2 Specific inspection requirements shall be established by the rotating hardware designer/ manufacturer with the concurrence of the DR.

4.9 Nondestructive Testing

4.9.1 Cryogenic Models: All materials used for critically stressed components for cryogenic model systems (excluding fasteners) shall be subjected to 100 percent volumetric nondestructive testing (NDT).

4.9.2 Non-cryogenic Models: Non-cryogenic model systems NDT requirements shall be established by the TPE/TE/RPE.

4.9.3 Metals:

4.9.3.1 Surface contact or immersion NDT methods may be used for ultrasonic inspection.

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

4.9.3.3 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."

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

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

4.9.4 Composite Material Inspection:

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

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

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

4.9.4.4 Other specialized techniques may be acceptable if approved by the DR/MSE/TPE/TE. Tap testing is a valuable screening/preliminary test, but has been superseded by new ultrasonic technology.

4.9.5 Inspection Personnel:

4.9.5.1 All inspection personnel shall be certified to Level II of the recommended practice of American Society for Nondestructive Testing (ASNT) Publication SNT-TC-1A or its equivalent.

4.9.5.2 Inspectors who perform tap tests shall be certified to Level-II in the ultrasonic inspection method.

4.10 Electrical Equipment And Components

4.10.1 General:

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.

4.11 Special Provisions For Model Systems Acceptance For Testing

4.11.1 Previous Tests

4.11.1.1 Models previously tested in the same and/or other facilities may be tested at NASA with facility DR 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 proposed NASA tests.

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

4.11.2 Static Load Tests

4.11.2.1 With DR approval, static load tests may be conducted in lieu of stress analysis. These tests shall 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.

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.

c. If 4.11.2. a. above is selected, plots of loads versus deflections for a complete loading cycle shall be included in the Model System Report.

4.11.3 Special Tests

4.11.3.1 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.

4.11.3.2 The DR shall approve the acceptability of models and/or components to be tested and/or used under the provisions of this section.

4.12 Force Balance Design and In-Service Inspections

4.12.1 Stress Analysis

4.12.1.1 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 4.4.

4.12.1.2 For a force balance utilizing Method 1 or 1A, the allowable stresses shall be determined according to the same criteria as described in Sections 4.4.3 and 4.4.3 (smaller of one-quarter (1/4) of the minimum ultimate strength or one-third (1/3) of the minimum yield strength of the material).

4.12.1.3 Since the loading in the balance is well understood, a Method 2 approach is more commonly used for force balances. For a method 2 analysis, the allowable stress table given in Section 4.4.7 shall be used to determine the combined stress intensity allowables.

4.12.1.4 As an alternative approach to computing the individual stress components required in Section 4.4.7, the allowable von Mises stress due to combined design loads on force balances utilizing Method 2 shall be established by Section 4.5.4.5.

4.12.1.5 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.

4.12.2 Fatigue and Fracture Analysis:

4.12.2.1 The highest stress points in the balance (e.g., 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.

4.12.2.2 Fracture analysis shall be required for cryogenic balances.

4.12.2.3 For a particular balance, the balance design review panel shall determine the fatigue analysis requirements, which may deviate from Appendix A and the fracture analysis requirements, which may deviate from Appendix B.

4.12.3 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.

4.12.4 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).

4.12.5 Testing Frequency

4.12.5.1 As a minimum, each balance shall be loaded to its combined load limit as defined in Section 4.12.4 within 12 months prior to the tunnel entry unless the balance has less than 1500 hours of tunnel use since it was last statically load tested.

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

4.12.6 Inspections

4.12.6.1 All balances shall be thoroughly inspected at time of manufacture, and at the same established intervals detailed in Section 4.12.5 for the presence of surface and internal cracks and defects, particularly in areas of stress concentrations and the control points as identified in Section 4.12.2.1.

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

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

4.12.7 Design Evaluations for Non Accessible Balances

4.12.7.1 For balances in which the control points specified in Section 4.12.2.1 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.

4.12.7.2 The evaluation shall include a fatigue life assessment considering past usage history, where available, based on stresses at the control points.

4.12.7.3 A containment system shall be identified which provides model retention in all failure modes of the balance identified in 4.13.3.

4.12.7.4 In the absence of sufficient information to perform the assessments in paragraphs 4.12.7.1 and 4.12.7.2, the FME shall derate the balance to establish safe working levels.

4.12.8 Maximum Loads

Balance design loads as established by the FME shall not be exceeded during the wind tunnel test.

4.12.9 Documentation

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

4.12.10 Reviews

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

4.12.11 Special Provisions for Balance Acceptance for Testing

4.12.11.1 In cases where the Balance Stress Analysis Report is unavailable or incomplete, either of the following sections may be applied with DR and FME approval:

a. Previous Tests

(1) Balances previously tested in the same and/or other facilities may be tested at NASA with facility DR approval.

(2) The request for approval for use shall include documented evidence that each of the three following conditions are satisfied:

(3) The balance has been tested to loads equal to or higher than anticipated in the proposed test.

(4) A fatigue evaluation that demonstrates the design life of the balance will not be exceeded during the proposed NASA test.

(5) Critically stressed components have undergone NDT prior to wind tunnel testing.

b. Static Load Tests

(1) 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.

(2) Plots of applied load versus balance deflection and electrical output for a complete loading cycle shall be included in the Balance Stress Analysis Report.

4.13 Automotive Vehicles

4.13.1 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 NASA wind tunnels if the following criteria are met. In situations where these criteria are not clear, the DR shall determine the appropriate criteria and document the determining rationale.

4.13.2 Vehicle Integrity

4.13.2.1 The preferred method of certifying a vehicle for testing shall be in compliance with the stress analysis methods described in Section 4. of this NASA Technical Standard.

4.13.2.2 However, if Section 4.13.2.1 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.

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

4.13.3 Vehicle Inspection

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

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

4.13.3.3 All components shall fit according to defined specifications.

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

4.13.4 Vehicle De-Fueled

4.13.4.1 The vehicle shall be de-fueled to a level consistent with only unusable fuel remaining in any fuel tank, hose, or fuel supply routing. This is usually achieved by running the engine until it stalls and cannot be re-started. Fuel leaks, visible or detected by olfactory methods, are not permitted.

4.13.4.2 A Safety Data Sheet (SDS) of the fuel shall be provided and the center Fire Chief or appropriate First Responder notified before the wind tunnel test starts.

4.13.4.3 Any proposed vehicle running tests shall include the center Fire Chief or appropriate First Responder as an additional approver in the waiver approval process.

4.13.4.4 Batteries: The preferred method of testing is to remove all batteries from the vehicle. 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 DR for safe installation practices. An emergency battery disconnection method may be requested to be demonstrated by the facility test engineer.

4.13.5 Corrosive Chemicals

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

4.13.6 Compressed Gases

All compressed gas (flammable or non-flammable) cylinders shall be removed from the vehicle unless demonstrated to be completely empty of pressure. This includes fire suppression systems.

4.13.7 Airbags

4.13.7.1 If airbags are present, they shall have their activation circuit disabled in a manner acceptable to the DR.

4.13.8 Vehicle Securing Systems

4.13.8.1 Two methods of securing the vehicle in the tunnel shall be used, as follows:

a. A brake pedal locking device is to 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.

c. Brake fluid levels and restraint strap condition shall be inspected before each day's test and upon tunnel entry during the test.

4.13.9 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.

4.13.10 Developing Risks

Any situation deemed to be an unacceptable risk by the Facility Test Engineer shall be examined by the DR for consideration of a solution.

5. CERTIFICATION OF MODELS, STINGS, AND OTHER MODEL MOUNTING HARDWARE

5.1 Introduction

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

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

5.2 New Sting and Model Mounting Hardware

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

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

5.2.3 Stings and associated hardware used infrequently (e.g., time between use is often greater than 1 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.

5.2.4 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.

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

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

5.3 Existing Equipment

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

5.3.2 Existing equipment shall be inspected at regular intervals, determined by the DR with the aid of the MSE.

5.3.3 Stings and associated hardware used infrequently (e.g., time between use is often greater than 1 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.

5.3.4 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.

5.4 Periodic In-Service Inspections of Calibration Models and Model Hardware

5.4.1 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.

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

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

5.5 Model Support Systems or Test Rigs Designed to this Standard

All systems and rigs designed to this standard shall be inspected prior to operation in the facility, to include:

a. All required systems are in place and fully functional.

b. If a maintenance plan exists for the system, all required maintenance has been performed.

c. If the configuration has been modified since the last installation, that all changes are properly documented and approved.

d. Any modifications to other tunnel systems will not interfere with the safe operation of the rig.

5.6 Mechanical Connections of Sting Taper Joints

5.6.1 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.

5.6.2 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.

6. QUALITY ASSURANCE

6.1 Introduction

6.1.1 This section provides detailed quality assurance criteria for wind-tunnel model systems to be tested at NASA.

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

6.2 Implementation Responsibility

6.2.1 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.

6.2.2 At a minimum, components identified as critically loaded/stressed (including fasteners) whose failure can result in critical or catastrophic facility damage/injury, as defined in this document, shall meet all requirements of this section.

6.2.3 Responsibility for determining specific quality assurance requirements and compliance for the different categories of model systems is assigned as follows:

a. NASA Provided: NASA TPE or RPE/TE, if a TPE is not assigned.

b. Contract: NASA 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 section 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 section.

(2) This documentation shall be included in the Model Systems Report (see Section 7) submitted to the DR.

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

6.3 Quality Assurance Criteria

6.3.1 Procurement

6.3.1.1 Purchase Orders

6.3.1.1.1 List of NASA Provided or NASA Procured Hardware

6.3.1.1.2 All purchase orders, for model systems parts and materials, to include fasteners and pins, shall identify procurement quality assurance and inspection acceptance criteria

6.3.1.2 Receiving Inspection

6.3.1.2.1 Receiving inspection and acceptance of hardware and all documentation thereof shall be the responsibility of the NASA TPE/RPE/TE ordering the hardware.

6.3.1.2.2 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.

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

6.3.1.3 Acceptance/Rejection of Procured Articles

6.3.1.3.1 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.

6.3.1.3.2 Articles, which do not conform to drawings or specifications and/or do not have adequate or correct data, shall be held for disposition.

6.3.1.4 Supplier Documentation

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

a. Material certification test report.

b. Evidence of supplier inspection acceptance

c. Certification of heat treatment process.

d. Certification that the end-item is from the material specified.

e. Test data.

f. Inspection reports.

g. Weld and Braze Qualification/Certification documentation as required by the purchase order.

h. Other documentation as specified on the purchase order.

6.3.1.5 Model Threaded Fasteners and Pins (NASA Procurred)

All safety critical products (including critical fasteners, pins, etc.) shall follow the requirements set forth in one of the following:

a. LAPD 4520.1, Langley Research Center (LaRC) Requirements for Safety-Critical Product Testing and LAPD 5330.3, Langley Research Center (LaRC) Standards for the Acquisition of Threaded Fasteners (Bolts).

b. A027-9391-XB2 Test Planning Guide for High Speed Wind Tunnels (ARC).

c. NASA/TM—2004-212706/REV1 NASA Glenn Wind Tunnel Model Systems Criteria.

6.3.2 Fabrication.

6.3.2.1 Traceability and Control

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

6.3.2.2 Controlled Storage

Critical raw materials, parts, and fasteners shall be stored in a dedicated, controlled-access storage area.

6.3.2.3 Configuration Control

6.3.2.3.1 Configuration of the end-item hardware shall be maintained by the TPE/RPE/TE through the control of drawing and specification changes.

6.3.2.3.2 The TPE/RPE/TE shall be responsible for assuring that obsolete drawings/specifications are withdrawn and destroyed.

6.3.2.4 Permanent Identification

6.3.2.4.1 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.

6.3.2.4.2 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.

6.3.2.4.3 The main model assembly shall be permanently marked with the model number assigned to that model.

6.3.2.4.4 Each model box shall be permanently marked with the model number assigned to that model.

6.3.2.5 Drawing and Specification Control

6.3.2.5.1 Drawings and specifications shall define the complete as-built configuration and provide a record of the design.

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

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

6.3.2.6 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.

6.3.2.7 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 by the TPE/RPE/TE.

6.3.2.8 Metrology Control

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

6.3.2.9 Handling, Packing, and Shipping

6.3.2.9.1 All hardware shall be protected from damage during all phases of manufacturing and shipping.

6.3.2.9.2 The TPE/RPE/TE shall document any special handling, packing, and shipping requirements for model system hardware and communicate with the supplier.

6.3.2.9.2.1 Shipping containers shall be designed to ensure safe arrival and ready identification.

6.3.2.9.3 Containers for finished hardware shall provide identification for individual parts.

6.3.2.9.4 Containers for finished hardware shall contain a complete set of as-built drawings, including assembly procedures.

6.3.2.10 Records

Upon completion of fabrication of the model system, the quality assurance records shall be incorporated into the Model System Report by the TPE/RPE/TE as required by Section 7.

6.4 User Furnished Hardware

6.4.1 Supplier Documentation

6.4.1.1 Evidence of the following required supplier inspections and tests, as defined in the purchase documentation, shall be verified at receiving inspection:

a. Material certification test report.

b. Evidence of supplier inspection acceptance.

c. Certification of heat treatment process.

d. Certification that the end-item is from the material specified.

e. Test data.

f. Inspection reports.

g. Weld and Braze Qualification/Certification documentation.

h. Other documentation as required.

6.4.2 Model Threaded Fasteners and Pins (User Supplied)

All safety critical products (including critical fasteners, pins, etc.) shall follow the requirements set forth in one of the following:

a. LAPD 4520.1, Langley Research Center (LaRC) Requirements for Safety-Critical Product Testing and LAPD 5330.3, Langley Research Center (LaRC) Standards for the Acquisition of Threaded Fasteners (Bolts).

b. A027-9391-XB2 Test Planning Guide for High Speed Wind Tunnels (ARC).

c. NASA/TM—2004-212706/REV1 NASA Glenn Wind Tunnel Model Systems Criteria.

6.4.3 Records

Upon delivery of the model system, the pertinent quality assurance records shall be incorporated into the Model System Report by the TPE/RPE/TE as required by Section 7.0.

7. DOCUMENTATION

7.1 Model Systems Report

7.1.1 A Model Systems Report (in English) shall be required for all model systems to be tested in mandatory NASA facilities as listed in Section 1.2.

7.1.2 The Model Systems Report shall be submitted by the NASA TPE and/or RPE/TE to the DR according to the schedule established by the DR.

7.1.3 In the absence of an established delivery date, the delivery shall take place at least 4 weeks prior to tunnel entry.

7.1.4 Contents

7.1.4.1 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, as follows:

(1) Model specifications/requirements.

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

(3) Fasteners.

(4) Life requirements.

c. The stress report (see Section 4.3.3). 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, as follows:

(a) Standard properties.

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

(c) Fasteners.

(5) Method of analysis, as follows:

(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). Both positive and negative maximums for parts with possible loading in both direction.

(6) Structural joint analysis, as follows:

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

(b) Welded.

(c) Brazed.

(d) Bonded.

(e) Pressurized systems analysis (if required).

(7) Pressure test results (if required).

(8) Specialized analysis (if required), as follows:

(a) Fatigue and fracture.

(b) Thermal.

(c) Finite Element.

(d) Hazard Analysis.

(9) Stability reports (if required), as follows:

(a) Divergence.

(b) Flutter.

(c) Dynamics.

(d) Buckling.

d. Inspection reports, as follows:

(1) Certification of materials.

(2) Inspection procedures.

(3) Nonconformance reports.

(4) Quality assurance report, including bolt pre-torques for critical joints.

e. Test reports (if required), as follows:

(1) Material properties.

(2) Loads tests.

(3) Modal survey.

(4) Static and dynamic balancing.

(5) Demonstration run-up.

(6) Deviation requests and supporting documents.

(7) Single Order Failure Risks and Interlocks Analysis.

(8) Design review documents, action items, and their disposition.

f. List of critically loaded/stressed components, as follows:

(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, etc.) for components whose failure can result in a critical or catastrophic failure.

7.1.5 Retention

7.1.5.1 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.

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

7.2 Assembly, Installation, and Configuration Change Procedures

7.2.1 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.

7.2.2 Delivery Schedule

Documentation of the procedures shall be submitted to the NASA RPE/TE no later than 4 weeks prior to the tunnel entry date, or according to the schedule established by the RPE/TE.

7.2.3 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 facility as well as permit model configuration changes during the test program.

8. DEVIATIONS

8.1 General

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

8.1.2 Relief to institutional safety requirements require evaluation from the Center Institutional Safety Discipline Leads (Pressure Systems Managers (PSM), Authority Having Jurisdiction (AHJ) for Fire Protection and Life Safety, Explosives Safety Officer (ESO), Safety Manager, Lifting Devices and Equipment Manager (LDEM), Fall Protection Program Administrator (FPPA), and Center Range Flight Safety Lead (CRFSL)) and approval from the Center Institutional Safety Authority in accordance with NASA NPR 8715.1.

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

8.2 Deviation Requests

8.2.1 The deviation request shall be submitted through the TPE/RPE/TE to the cognizant DR.

8.2.2 The DR shall be responsible for providing or obtaining the evaluation of the rationale for the deviation. In performing this evaluation, the DR may request assistance from the FME, MSE, NASA organizational elements, or other committees, as required, to verify the adequacy of technical assessments and acceptability of additional risks.

8.2.3 An information copy of all deviation requests and their disposition shall be submitted to the Center's Safety and Mission Assurance Office.

8.2.4 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.

8.3 Approval Authority

8.3.1 In instances where a model system failure could be expected to result in a risk level of RAC-3 or less, the DR shall be authorized to approve deviation requests.

8.3.2 For failure situations that could be expected to cause risk level higher than RAC-3, up to RAC-2, the NASA official (LaRC Organizational Unit Manager, ARC Director of Aeronautics, GRC Safety Committee Head) of the involved facility shall approve all deviations.

8.3.3 In any instance where the risk level is higher than RAC-2 in the event of a model system failure, concurrence shall be through the NASA Center Deputy Director.

APPENDIX A. FATIGUE DESIGN

A.1 Purpose

The purpose of this appendix is to define the procedure for completing a fatigue analysis.

A.2 Alternating Stress Defined

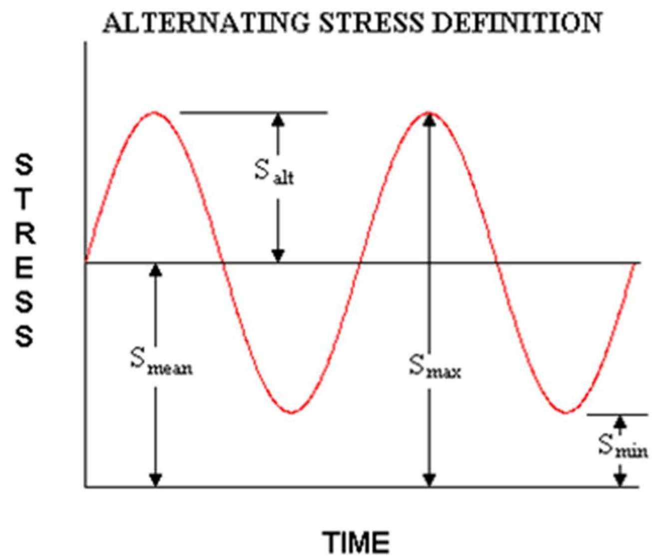

Figure A-1. Alternating Stress Definition

A.2.1 Given the above illustration of a fluctuating stress around a mean value, the definitions needed to perform a fatigue analysis are as follows:

S_{min} = minimum stress

S_{max} = maximum stress

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

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

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

A.2.2 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.

A.3 Fatigue Curve

A.3.1 When available, fatigue (S-N) data for the material at test temperature is to be used. However, when S-N data are not available, a general rule of thumb for the average endurance limit Se, (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:

Note: (Mean endurance limit of the rotating beam specimens)

Steel Alloys	Aluminum and composites
Se ≤ 0.5 Su where Su ≤ 200 Ksi	Se ≤ 0.3 Su
Se ≤ 100 Ksi where Su > 200 Ksi	

A.3.2 As a rule, a design, which is within the allowables of Method 1 (Section 4.4.3) will usually, provide a safe-life (usually infinite) design. However, this should not preclude the designer from calculating the fatigue life of the system.

A.3.3 An example of a typical S-N curve is as follows:

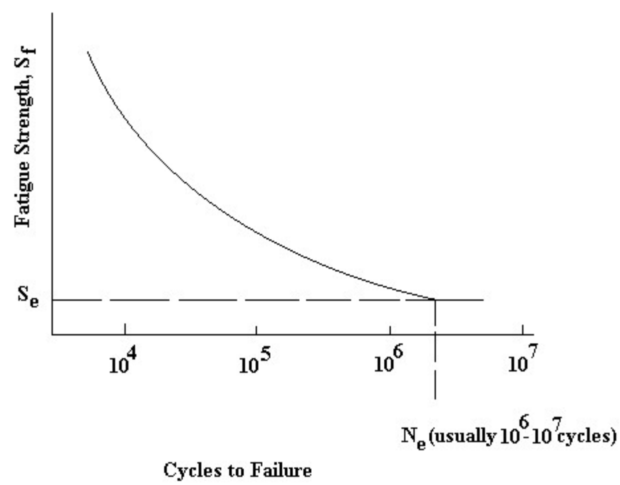

Figure A-2. Typical S-N Curve

A.4 Application

A.4.1 Fatigue Strength Modifying Factors

A.4.1 In computing the fatigue life, fatigue endurance limit modifying (reduction) factors are to be applied to the appropriate fatigue curve. Modifying factors to be considered are as follows:

a. Surface Finish Factor.

b. Scale Factor.

c. Reliability Factor (for example, R = 0.00000, Kr = 0.659).

d. Temperature Factor.

e. Other miscellaneous factors as required.

Note: A fatigue strength modifying factor of K = 0.5 may be used to cover items a. through f.

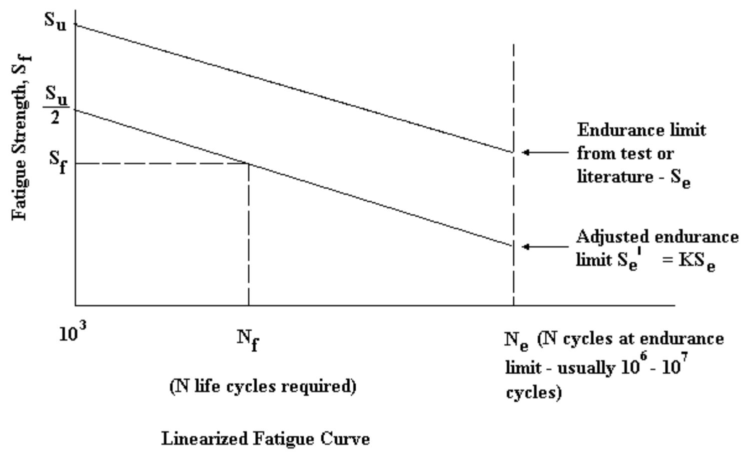

Figure A-3. Linearized Fatigue Curve

A.4.2 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 are to 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.

A.4.3 Effects of Mean Stress

A.4.3.1 Next, to account for the effect of mean stress (S_{mean}), a modified Goodman diagram is to be constructed to determine the allowable alternating stress, S_a. The procedure is as illustrated as follows:

A.4.3.1.1 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.

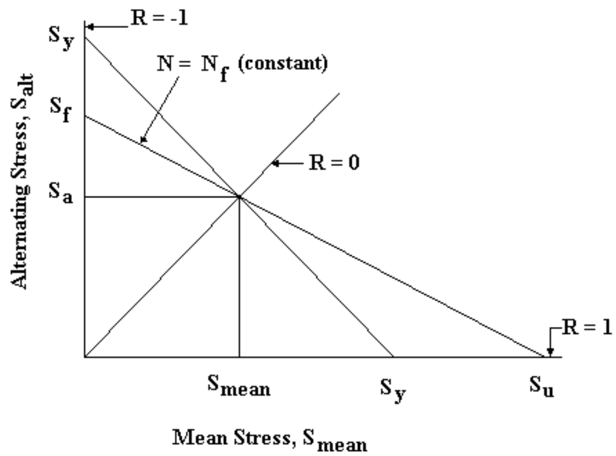

Figure A-4. Goodman Diagram

a. Case 1

For

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

b. Case 2

For

Equation-2

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

Where

Equation-3

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

And

Equation-4

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

Note: For applicability of fatigue analysis requirements to wind tunnel balances, reference Section 4.13.2.

APPENDIX B. FRACTURE MECHANICS ANALYSIS

B.1 Purpose

The purpose of this appendix is to define the procedure for completing a linear elastic plane strain fracture mechanics analysis.

B.2 Fracture Crack Growth Assessment

B.2.1 General

B.2.1.1 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.

B.2.1.2 When no cracks are detected during NDT inspections, the largest crack that can be missed by a crack inspection is to be assumed present to ensure conservative predictions. A conservative fatigue life prediction is then used to establish regular inspection intervals. Multiple inspections are planned during the fatigue life so missing a fatigue crack during a single inspection does not cause catastrophic failure. DT is the most conservative fatigue life management method, but inspection for cracks, especially small ones, is an expensive and time consuming process. These extra efforts are warranted for scenarios where failure must be avoided (e.g. critically stressed parts where failure may cause injury or destroy expensive equipment). Less rigorous life management methods may be the best life management method for non-critical or inexpensive parts where periodic part replacement is a cost-effective option.

B.2.1.3 The fatigue life criteria prescribed in this appendix provide three levels of analysis that allow the designer to meet the fracture criteria required in this document. Level one defines two ways to establish the fracture toughness with all applied stresses causing damage. Level two employs a fatigue-crack-growth threshold which defines a stress intensity level where cracks do not propagate thus prescribing a less conservative approach for calculating fatigue life. Level three allows the designer the option of using a commercially available fatigue-crack-growth computer code.

Note: For applicability of fracture analysis requirements to wind tunnel balances, reference Section 4.13.2.

B.2.2 Required Data

B.2.2.1 In order to perform a fracture mechanics analysis, it is necessary to have fatigue crack growth and fracture data set at operating conditions, and knowledge of the component stresses and NDT inspection method. The required data, and the preferred order of the source from which to obtain the data is as follows (in each list, data source "1" is the optimum source for the data):

a. ΔK_{Ic} fracture toughness data.

(1) Test data generated from the specific material by the manufacturer, per ASTM E399, at operating temperature.

(2) Test data found in literature that matches the heat treat, material chemistry and operating temperature with the integrity requirements of Section 4.2.5.

(3) For Steel Alloys Only, Charpy V-Notch data may be used per appendix section B.4.

(4) If (1)-(3) are not feasible, the manufacturer is to generate fracture toughness data per ASTM E399 at the operating temperature.

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

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

(2) Test data found in literature that matches the heat treat, material chemistry and operating temperature with the integrity requirements of Section 4.2.5.

(3) If b(1) and b(2) . are not feasible, the manufacturer is to generate fatigue crack growth data (da/dN vs. ΔK) per ASTM E647 at the operating temperature.

(4) If the fracture analysis method given in Section B.2.3 is used, no fatigue crack growth data is needed.

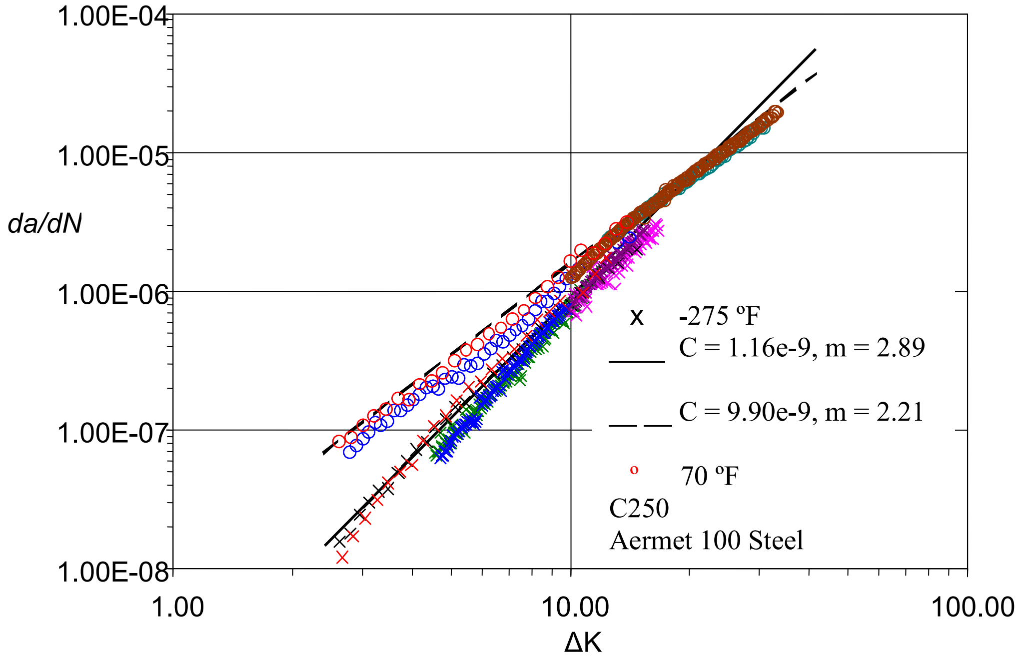

Figure B-1. Fatigue Crack Growth Data (da/dN vs. ΔK) and Curve Fits for Two Steels at 70 *ºF* and –275 *ºF*

c. S_{max}, S_{min} maximum and minimum applied stress per cycle

B.2.2.2 The stress levels are defined in Section 4.5.4.3 and illustrated in Figure B-2, Schematic of Cyclic Stresses.

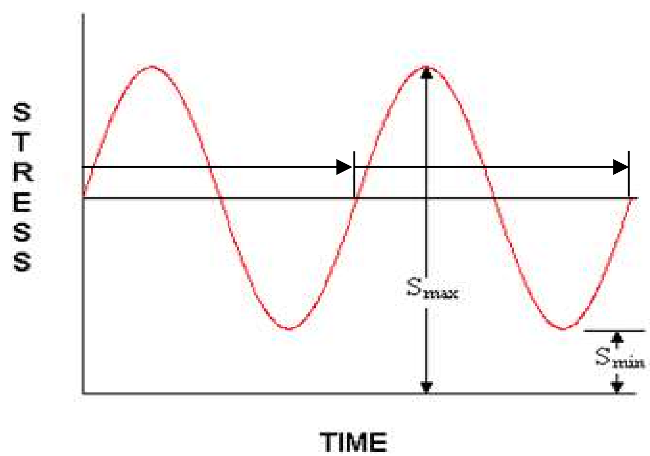

Figure B-2. Figure 2 Schematic of Cyclic Stresses

B.2.2.3 Value a_i initial crack size defined by nondestructive inspection (NDT) (Section 4.10 and Table 2, Typical Initial Crack Sizes for Fracture Analysis Based on NDT Methods).

(ref: Fracture Control Requirements for Space Station, SSP 30558, Rev. B)

Table B-1. Typical Initial Crack Sizes for Fracture Analysis Based on NDT Methods

NDT 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.

B.2.3 Fracture Analysis Method

B.2.3.1 To assess the life of a component, fatigue crack growth data (da/dN, vs. ΔK), fracture toughness data (K_{Ic}), and knowledge of the NDT methods 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 NDT crack size shown in Table B-1 based on the inspection method. To compute the life of the component from this crack, a relation between crack growth rate, da/dN, and the stress intensity factor range, ΔK, is used such that.

Equation-5

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

Where

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

And,

Equation -7

$$R = \frac{S_{min}}{S_{max}}$$

S_{max} and S_{min} define the maximum stress and minimum stress in the load cycle (see Figure B-2), and *C* and *m* are considered to be material constants. Experimental data are used to determine *C* and *m* such that a straight line fits the data on a log-log scale as shown in Figure B-1. Extensive data for the material constants *C* and *m* for a variety of metals can be found in the technical literature, such as those listed in Section 4.2.6.1. As an alternative, the analyst may use the following relation where *E* is the elastic modulus.

Equation **- 8**

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

B.2.3.2 The stress intensity range is defined as

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

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,

Equation-10

$$K_{Ic} = S_{max}\sqrt{\pi a_c}$$

or

Equation-11

$$a_c = \frac{1}{\pi}\left(\frac{K_{Ic}}{S_{max}}\right)^2$$

B.2.3.3 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.

Equation-12

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

B.2.3.4 Substituting equation (8) into equation (12), and solving for da yields.

Equation-13

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

B.2.3.5 Solving equation (13) 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.

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

B.2.3.6 To complete the fracture analysis, an inspection interval is to be established. In the fracture analysis prescribed herein, there should be at least seven NDTs for cracking during the operational life of the component. Therefore, the total life is divided by eight, and the inspection interval is defined as

$$Inspection\ Interval = \frac{N_{tot}}{8}$$

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

B.2.4 Three Level Fracture Analysis

B.2.4.1 Use the fatigue crack growth methodology outlined in the previous section. The fatigue life requirement is met by two criteria:

B.2.4.1.1 The critical crack size is to be at least four times the NDT initial crack size.

Equation **- 15**

$$a_c \geq 4a_1$$

B.2.4.1.2 The total fatigue life, divided by a factor of safety of two, should give enough operating time to perform all required experiments and allow reasonable operating time between NDTs, *i.e.*:

Equation **- 16**

$$Inspection\ Interval = \frac{N_{tot}}{8}$$

B.2.4.2 If no damage is found in the component during an inspection, the load history is erased and the part is assumed to be new. Figure B-3, Schematic Illustrating Damage-Tolerance Fatigue Life Management, depicts this concept.

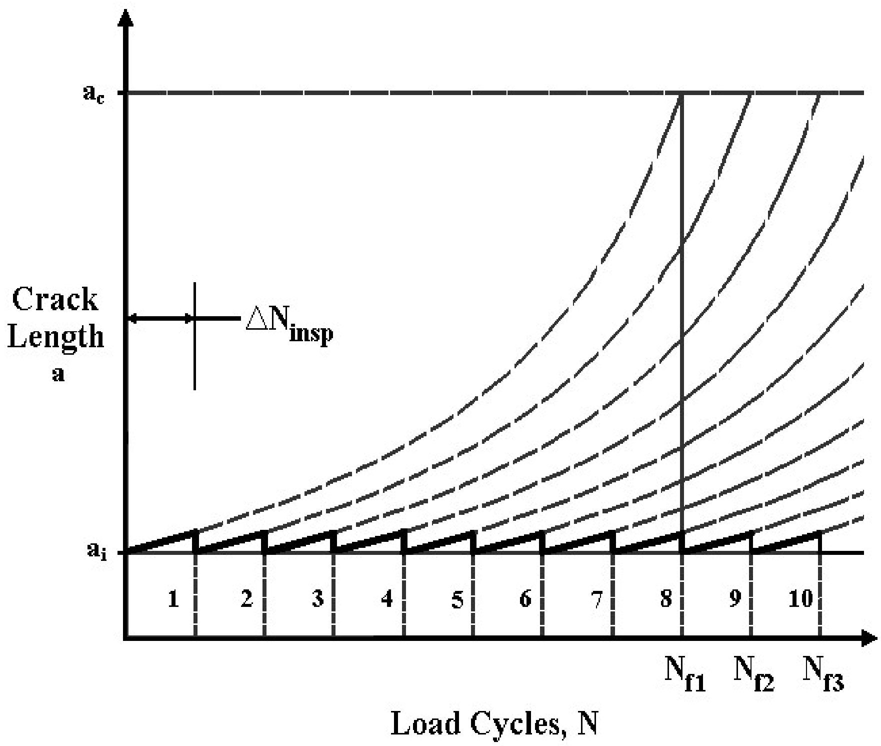

Figure B-3. Schematic Illustrating Damage-Tolerance Fatigue-Life Management

B.2.4.3 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.

B.2.4.4 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} is not to exceed 1.2 times K_{Ic}, where K_{Ie} is defined as

Equation-17

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

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 is to be met.

B.2.4.5 Level 2

B.2.4.5.1 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.

Equation-18

$$\Delta K_{th} = 0.000\,UE$$

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

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

B.2.4.6 Level 3

B.2.4.6.1 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:

B.2.4.6.1.1 The material data used (da/dN vs. ΔK, K_{Ic}, K_{Ie} and ΔK_{th}) is to meet the integrity requirements outlined in B.1b.

B.2.4.6.1.2 The geometry is to be representative of the component under investigation.

B.2.4.6.1.3 The initial NDT 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 2, and the shape of the crack is to be an aspect ratio (*a/c*) of 1.

B.2.4.6.1.4 The fatigue crack growth analysis is to be rigorously documented with reference material on the stress intensity factor solution, loading information and material data used.

B.2.4.6.1.5 The critical crack size requirement and factor of safety on total fatigue life defined in equations (15) and (16) are to be met. If the analysis cannot meet these requirements a reassessment of the loads, component geometry and/or material may be required.

B.3 Example of Life Calculation

B.3.1 Assume a part for cryogenic operation (–275 ºF) is being designed for operation in a NASA wind tunnel. A material is selected and a stress analysis has been completed. To perform the fracture analysis, the 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 ºF are expressed as:

$$C = 1.16x10\text{-}9, m = 2.89, K_{Ic} = 65 \text{ ksi in}^{1/2}$$

B.3.2 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.

B.3.3 Dye penetrant has been chosen for NDT after every 10 runs which gives an initial crack size of ai = 0.100 in. and an inspection interval of N_{insp} = 500 cycles.

B.3.4 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 (11) 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 (14) where

Equation - 20

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

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

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

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

B.3.4.1 For the first cycle, j=1

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

B.3.4.2 For the second cycle, j=2

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

B.3.4.3 For the third cycle, j=3

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

B.3.5 Hence, after three cycles, the crack length is 0.100036 inches. Continuing this summation, the part will fail at approximately 29,000 cycles.

B.3.6 To meet the Level 1 requirements, the critical crack size is required to be at least four times the NDT crack size and the inspection intervals and total life, with a safety factor of two, need to be manageable.

$$Inspection\ Interval = \frac{N_{tot}}{8} = \frac{29{,}000}{8} = 3{,}625$$

B.3.6.1 The safe predicted life of 14,500 exceeds the design life of 5,000 cycles.

B.3.6.2 The predicted inspection interval 3,625 exceeds the desired inspection of 500 cycles.

B.3.6.3 The critical crack size of 0.374 inches is less than 4 times the NDT crack size of 0.100 inches.

B.3.7 The design fails the critical crack size requirement as prescribed in Section B.1e.

B.3.8 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 (17), the K_{Ie} is defined as

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

B.3.8.1 Therefore, KIe = 78.0 ksi-in^{½}.

B.3.9 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 ac = 0.538 in.

B.3.10 To meet the two criteria for fatigue life in Section B.1d, the critical crack size is to be at least four times the NDT crack size and the inspection intervals and total life, with a safety factor of two, are to be manageable.

$$Inspection\ Interval = \frac{N_{tot}}{8} = \frac{46{,}158}{8} = 5{,}759\ cycles$$

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

B.3.10.1 The safe predicted life of 23,079 exceeds the design life of 5,000 cycles.

B.3.10.2 The predicted inspection interval 5,769 exceeds the desired inspection of 500 cycles.

B.3.10.3 The critical crack size of 0.538 inches is more than 4 times the NDT crack size of 0.100 inches.

B.3.10.4 This design analysis meets the two criteria requirements for fatigue life.

B.4 Charpy V-Notch (CVN) Relations for Steel Alloys

B.4.1 In cases where K_{Ic} data is not available, an empirical relation exists for ferritic and martensitic steels which relates plane strain fracture toughness to Charpy impact energy (see Barsom & Rolfe, S. T., 1970). 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 CVN is the impact energy, (ft-lb).

B.4.2 The CVN 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 is to include two independent sources of data and be from a reputable resource such as those defined in Section 4.2.6.1.

B.4.3 "This relationship, while questionable for high-toughness austenitic steels, appears to give good correlation for ferritic and martensitic steels." (See NASA-TM-85816.)

APPENDIX C. STRESS REPORT FORMAT

C.1 Purpose

The purpose of this appendix is to provide direction on the contents and organization of a Wind Tunnel Model Stress Report.

C.2 General

C.2.1 The Wind Tunnel 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 test engineer to use during the testing if circumstances arise where the loads are higher than predicted, or if the research engineer wishes to expand the envelope of testing. 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.

C.2.2 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.

C.3 Table of Contents

A Table of Contents should be included to permit the user to readily find the desired information. Not every subheading needs to be included, but sufficient detail should be included to provide direction to particular information.

C.4 Section 1, Introduction

C.4.1 This section should include 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 should also include a statement of the type of test (flutter, pressure, force, and moment), testing location(s), and test condition range.

C.4.2 If possible, an illustration serves well to orient the reviewer and subsequent users with the nomenclature used for the model segments, as well as presenting an easily understood overview of the model.

C.4.3 The last information to be included in the introduction is the type of analysis being presented (handbook versus FEA) and a very brief conclusion (i.e., “The model meets the requirements of …”).

C.4.3.1 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.

C.4.3.2 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 should include the model drawings, but can also include drawings of interface hardware such as stings and balances.

C.5 Section 2 - Reference Data

C.5.1 This section includes all relevant reference data, with source information, that is needed to support the analysis.

C.5.1.1 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 source of the data.

C.5.1.2 Section 2.2 – Fastener Specifications

C.5.1.2.1 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 versus flat head), strengths, and manufacturer's recommended tightening torques.

C.5.1.2.2 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 should be included in Section 2.1.

C.5.1.3 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.

C.6 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 should be defined here.

C.6.1 Section 3.1, 3.2… 3.n

C.6.1.1 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.

C.6.1.2 These sections should include a brief description of the part, its relationship to its neighbors, and the loading. Diagrams of the parts such as free-body diagrams should be included as required for clarity.

C.6.1.3 Equations should be listed in the first step prior to substitution of values. The values should then be substituted and the result listed. If the analysis is suited for tabular presentation, such as with Excel, then the first calculation should be presented completely, then the table with the sample calculation results included along with the balance of the calculations results.

C.7 Section 4 – Stress Analysis

This section includes the actual stress calculations for the components and their fasteners.

C.7.1 Section 4.1, 4.2…4.n

C.7.1.1 The analysis of each 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.

C.7.1.2 Subheadings should be 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.

C.7.1.3 Equations should be listed in the first step prior to substitution of values. The values should then be substituted and the result listed. If the analysis is suited for tabular presentation (such as with Excel), then the first calculation should be presented completely, then the table with the sample calculation results included along with the balance of the calculations results.

C.7.1.4 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.

C.7.1.5 When FEA is utilized in the analysis of the parts, a discussion of the numerical model is presented as well as its constraints, loading, and results. Also, verification of the results and model convergence need to be included. The analyst needs to be sure that sufficient information is included to allow the reviewer or user to know what is the high stressed area, as well as other significant areas that may also become critical. The high stresses that may show up around constraints may be written-off as modeling errors, so the next higher stresses become the important values. Remember that the analyst can rotate, view, and interrogate the numerical model as much as they want. The reviewer or user has only what is presented.

C.8 Section 5 – Other Analyses

C.8.1 This section is typically used for calculations such as divergence, fracture, and fatigue. Any other supplementary analyses can be included as required.

C.8.2 As with the preceding sections, sufficient information should be presented to frame the problem, show the analysis, and list results and any discussion that may be required.

C.9 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.