AIAA
S-110-2005

Standard

Space Systems – Structures, Structural Components, and Structural Assemblies

AIAA
S-110-2005

Standard

Space Systems — Structures, Structural Components, and Structural Assemblies

Sponsored by

American Institute of Aeronautics and Astronautics

Approved

12 July 2005

Abstract

This document establishes a standard for the design, analysis, material selection and characterization, fabrication, test, and inspection of structural items in space systems, including payloads, spacecraft, upper-stages, and expendable and reusable launch vehicles. This standard, when implemented on a particular space system, will assure high confidence in achieving safe, reliable operation in all phases of the mission. This document applies specifically to all structural items including fracture-critical hardware used in space systems during all phases of the mission—with the following exceptions: adaptive structures, engines, solid rocket nozzles, and thermal protection systems.

Library of Congress Cataloging-in-Publication Data

Standard space systems : structures, structural components, and structural assemblies / sponsored by American Institute of Aeronautics and Astronautics.
p. cm.
"AIAA S-110-2005."
Includes bibliographical references and index.
ISBN 1-56347-770-X (hardcopy : alk. paper) -- ISBN 1-56347-771-8 (electronic : alk. paper)
1. Space vehicles--Standards. 2. Aerospace industries--Materials--Standards. I. American Institute of Aeronautics and Astronautics.

TL795.S73 2005
629.47'02'1873--dc22

2005012640

Published by
American Institute of Aeronautics and Astronautics
1801 Alexander Bell Drive, Reston, VA 20191

Printed in the United States of America

Contents

Tables

Foreword

This standard was prepared by the AIAA Structures Committee of Standards (CoS) based on an Aerospace Technical Operating Report, TOR-2003 (8583)-2894, Space Systems-Structures Design and Test Requirements, 2 August 2004.

The AIAA Structures CoS was formed in 2004 with an emphasis on inclusion of experts in aerospace industry, academia, and interested government agencies. Deliberations focused heavily on adapting this standard to new space systems not only developed for the United States Air Force/Space and Missile Systems Center (USAF/SMC) but also for civil and commercial applications.

At the time of approval, the members of the AIAA Structures CoS were:

Pravin Aggarwal	NASA Marshall Space Flight Center
Basem Alzahabi	Kettering University
Steve Brodeur, Chair	Swales Aerospace
Meredith Cawley, Liaison	AIAA
Jim Chang, Co-Chair	The Aerospace Corporation
Sean Coghlan	Air Force Research Laboratory
Vinay Dayal	Iowa State University
Bob Farahmand	The Boeing Company
Anindya Ghoshal	United Technologies Research Center
Hector Gomez	Northrop Grumman
Norman Knight	General Dynamics – Advanced Information Systems
Larry Loh	Lockheed Martin Corporation
Nat Patel, Co-Chair	The Aerospace Corporation
William Schonberg	University of Missouri-Rolla
Larry Trilling	Ball Aerospace & Technologies Corporation
Chris Wright	Lockheed Martin Corporation

The above consensus body approved this document in June 2005.

The AIAA Standards Executive Council (Mr. Amr ElSawy, Chairman) accepted the document for publication in July 2005.

The AIAA Standards Procedures dictate that all approved Standards, Recommended Practices, and Guides are advisory only. Their use by anyone engaged in industry or trade is entirely voluntary. There is no agreement between industry or trade, in general or specific, and AIAA to adhere to any AIAA standards publication and no commitment to conform to or be guided by standards reports. However, should a procuring authority choose to use this standard and contractually impose it upon a contractor and/or subcontractor, the use of this standard will be as defined by that particular contract.

In formulating, revising, and approving standards publications, the committees on standards will not consider patents that may apply to the subject matter. Prospective users of the publications are responsible for protecting themselves against liability for infringement of patents or copyright or both.

1 Scope

This document establishes a standard for the design, analysis, material selection and characterization, fabrication, test, and inspection of structural items in space systems, including payloads, spacecraft, upper-stages, and expendable and reusable launch vehicles. This standard, when implemented on a particular space system, will assure high confidence in achieving safe, reliable operation in all phases of the mission. This document applies specifically to all structural items including fracture-critical hardware used in space systems during all phases of the mission—with the following exceptions: adaptive structures, engines, solid rocket nozzles, and thermal protection systems.

2 Tailoring

For a specific program or project, the requirements defined in this Standard may be tailored to match the actual requirements of the particular program or project. Tailoring of requirements shall be undertaken in agreement with the procuring authority where applicable.

Tailoring is a process by which individual requirements or specifications, standards, and related documents are evaluated and made applicable to a specific program or project by selection, and in some exceptional cases, modification and addition of requirements in the standards.

3 Applicable Documents

The following applicable documents contain provisions which, through reference in this text, constitute provisions of this standard.

Aerospace TOR-2003 (8583) - 2886	*Aerospace Technical Operating Report, Independent Structural Loads Analyses of Integrated Spacecraft/Launch Vehicle Systems*
ANSI/AIAA S-080	*Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components*
ANSI/AIAA S-081	*Space Systems - Composite Overwrapped Pressure Vessel (COPVs)*
ANSI/AIAA S-096	*Space Systems - Flywheel Rotor Assemblies*
ASTM E-8	*Test Methods for Tension of Metallic Materials*
ASTM E-9	*Test Methods for Compression Testing of Metallic Materials at Room Temperature*
ASTM E-399	*Test Method for Plane Strain Fracture Toughness of Metallic Materials*
ASTM E-647	*Test Method for Measurement of Fatigue Crack Growth Rates*
ASTM E-740	*Practice for Fracture Testing with Surface-Crack Tension Specimens*
DOD/NASA	*Advanced Composites Design Guide, Vols. 1-4*
DOT/FAA/AR-MMPDS-01	*Metallic Materials Properties Development and Standardization*
ISO 21347	*Space Systems-Fracture and Damage Control*
MIL-HDBK-17	*Military Handbook, Polymer Matrix Composites, Vols. 1-5*

MIL-STD-1540	*Military Standard, Test Requirements for Launch, Upper Stage, and Space Vehicles*
MCIC-HB-01	*Damage Tolerance Design Handbook*
NASA-STD-5002	*Loads Analysis of Spacecraft and Payloads*
NASA-STD-5007	*General Fracture Control Requirements for Manned Spaceflight Systems*
NSS 1740.14	*Guidelines and Assessment Procedures for Limiting Orbital Debris*

4 Vocabulary

4.1 Acronyms and Abbreviated Terms

ε-N	Fatigue Strain-Life Data
Σ n/N	Miner's rule
AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standard Institute
ASTM	American Society for Testing and Materials
COPV	Composite Overwrapped Pressure Vessel
da/dN	Fatigue crack growth rate
CINDAS	Center for Information and Numerical Data Analysis and Synthesis
DOD	Department of Defense
DOT/FAA/AR	Department of Transportation/Federal Aviation Administration/Aviation Research
EVA	Extra-Vehicular Activity
FS	Factor of Safety
HDBK	Handbook
Hz	Hertz
ICD	Interface Control Document
ISO	International Organization for Standardization
KPP	Key Process Parameter
LBB	Leak-Before-Burst
MCIC	Metals and Ceramics Information Center
MEOP	Maximum Expected Operating Pressure
MEOS	Maximum Expected Operating Speed
MIL	Military

MMPDS	Metallic Materials Properties Development and Standardization
M/OD	Meteoroid and Orbital Debris
MS	Margin of Safety
NASA	National Aeronautics and Space Administration
NDE	Nondestructive Evaluation (Examination)
NDI	Nondestructive Inspection
NSS	NASA Safety Standard
S-N	Fatigue Stress-Life Data
VDT	Visual Damage Threshold

4.2 Terms and Definitions

For the purposes of this document, the following terms and definitions apply.

A-Basis Allowable
the mechanical strength value above which at least 99% of the population of values is expected to fall, with a confidence level of 95%

Acceptance Tests
formal tests conducted on flight hardware to ascertain that the materials, manufacturing processes, and workmanship meet specifications and that the hardware is acceptable for the intended usage

Adaptive Structures
autonomous structural systems which incorporate sensors, processors, and actuators to enable adaptation to changing environmental conditions, thereby enhancing safety, stability, vibration damping, acoustic noise suppression, aerodynamic performance and optimization, pointing accuracy, load redistribution, damage response, structural integrity, etc.

Allowable Load
the maximum load (force, stress, and/or strain) that can be accommodated by a structure or a component of a structural assembly without potential rupture, collapse, or detrimental deformation in a given environment

NOTE Allowable loads (forces, stresses, and/or strains) commonly correspond to the statistically-based ultimate strength, buckling strength, and yield strength.

B-Basis Allowable
the mechanical strength value above which at least 90% of the population of values is expected to fall, with a confidence level of 95%

Buckling
a failure mode in which an infinitesimal increase in the load could lead to sudden collapse or detrimental deformation of a structure

Catastrophic Failure
a failure which results in the loss of human life or mission

Collapse
the failure mode under quasi-static loads accompanied by very rapid irreversible loss of load-carrying capability

Composite Material
a combination of materials different in composition or form

NOTE 1 The constituents retain their identities in the composite.

NOTE 2 Normally the constituents can be physically identified, and there is an interface between them.

Composite Overwrapped Pressure Vessel (COPV)
a pressure vessel with a fiber-based composite system fully or partially encapsulating a liner

NOTE 1 The liner serves as a fluid permeation barrier and may or may not carry substantial pressure loads.

NOTE 2 The composite overwraps generally carry pressure and environmental loads.

Damage Tolerance
the ability of a structure or a component of a structural assembly to resist failure due to the presence of flaws, for a specified period of unrepaired usage

Design Safety Factor
a factor by which limit loads are multiplied in order to account for uncertainties and variations that cannot be analyzed or accounted for in a rational manner

NOTE Design safety factor is often referred to as design factor of safety or just factor of safety (FS).

Detrimental Deformations
all structural deformations, deflections, or displacements that prevent any portion of the structural item from performing its intended function

Development Test
a test to provide information that may be used to check the validity of analytic technique and assumed design parameters, uncover unexpected system response characteristics, evaluate design changes, determine interface compatibility, prove qualification and acceptance procedures and techniques, check manufacturing technology, or establish accept/reject criteria

Fail Safe Structure
a structural item designed with sufficient redundancy such that failure of one of its elements does not result in a catastrophic failure. In addition, the failure of the structural item must not release any potentially catastrophic free body.

Fatigue Life
the number of cycles of stress or strain of a specified character that a given structure or component of a structural assembly can sustain (without the presence of flaw) before failure of a specified nature could occur

Flaw
a local discontinuity in a structural material such as a crack, cut, scratch, void, delamination, disbond, impact damage, or other mechanical damage

Fracture Control
the application of design philosophy, analysis methods, manufacturing technology, verification methodology, quality assurance, including nondestructive evaluation (NDE) and operating procedures to prevent premature structural failure due to the propagation of flaws during fabrication, testing, transportation, handling, and service events such as launch, on-orbit operation, and return.

Fracture-Critical Part
a structural part whose failure due to the presence of a flaw would result in a catastrophic failure

Hydrogen Embrittlement
a mechanical-environmental process that results from the initial presence or absorption of excessive amounts of hydrogen in metals, usually in combination with residual or applied tensile stresses

Limit Load
the highest expected load or combination of loads that a structure or a component in a structural assembly may experience during its service life in association with the applicable operating environments

NOTE The corresponding stress is called limit stress.

Loading Case
the particular condition of load/pressure/temperature, which can occur for some structures or components of a structural assembly at some time during their service lives

Loading Spectrum
a representation of the cumulative loading levels and associated cycles anticipated for the structure or component of a structural assembly under all expected operating environments

NOTE Significant transportation, test, and handling loads are included.

Margin of Safety (MS)
MS = [Allowable Load (Yield or Ultimate)/Limit Load x Factor of Safety (Yield or Ultimate)] -1

NOTE 1 Load may mean force, stress, or strain.

NOTE 2 Definition applies to a single loading condition (mechanical, thermal, or pressure).

Maximum Expected Operating Pressure (MEOP)
the maximum pressure that pressurized hardware is expected to experience during its service life in association with its applicable operating environments

NOTE MEOP includes the effects of temperature, transient peaks, vehicle acceleration, and relief valve tolerance.

Metallic Structural Items
structural items made of metals

NOTE In this document, load bearing metallic liners of COPVs are also referred to as metallic structural items.

Moving Mechanical Assembly (MMA)
a mechanical or electromechanical device that controls the movement of one mechanical part of a vehicle relative to another part

EXAMPLES Gimbals, actuators, despin and separation mechanisms, motors, latches, clutches, springs, dampers, or bearings.

Pressure Vessel
a container designed primarily for storage of pressurized fluid that (1) contains gas or liquid with an energy level of 14,240 foot-pounds (19,310 joules) or greater, based on adiabatic expansion of a perfect gas; or (2) contains gas or liquid that will create a mishap (accident) if released; or (3) will experience a MEOP greater than 100 psi (700 kPa)

NOTE Pressurized structures, pressure components, and special pressurized equipment including batteries, heat pipes, sealed containers, and cryo-coolers are excluded.

Pressurized Structure
a structure designed to carry both internal pressure and vehicle structural loads

EXAMPLES Launch vehicle main propellant tanks, solid rocket motors, and crew cabins of manned modules.

Proof Factor
a multiplying factor applied to the limit load or MEOP to obtain proof load or proof pressure for use in the acceptance test program

Protoqualification Test
a test of the flight production unit to a higher load level and duration than acceptance, but less than qualification

NOTE 1 The testing consists of the same types and sequences as are used in qualification testing.

NOTE 2 The protoqualification test is conducted on a flight unit.

Qualification Tests
the required formal contractual tests conducted at load levels and durations sufficient to demonstrate that the design, manufacturing, and assembly of flight-quality structures have resulted in hardware that conforms to specification requirements

Residual Strength
the maximum value of load and/or pressure that a flawed or damaged structural item is capable of sustaining without further damage or collapse

S-Basis Allowable
the mechanical strength value which represents the specification minimum value specified by the governing industry specification or federal or military standards for the material, or a specified contractor quality-control requirement

Safe Life
the required period during which a structural item, even containing the largest undetected flaw, is shown by analysis or testing not to fail catastrophically under the expected service loads and environments

Service Life
the period of time (or cycles) beginning with the manufacturing of the structural item and continuing through all acceptance testing, handling, storage, transportation, launch operations, orbital operations, refurbishment, retesting, reentry or recovery from orbit, and reuse that may be required or specified for the item

Stress-Corrosion Cracking
a mechanical and environmentally induced failure process in which sustained tensile stress and chemical attack combine to initiate and propagate a crack or a crack-like flaw in a metal part

Stress-Rupture Life
the minimum time during which a nonmetallic structural item maintains structural integrity, considering the combined effects of stress level(s), time at stress level(s), and associated environments

Structural Component
mechanical part(s) in a functional hardware item designed to sustain load and/or pressure or maintain alignment

EXAMPLES Antenna support structure, instrument housing, pressure vessel, and solid rocket motor case.

Structural Item
a structure, a structural subsystem (assembly), or a structural component

Structural Mathematical Model
an analytical or numerical representation of a structure

Structural Subsystem (Assembly)
a mechanical subsystem or assembly that is designed to carry primary vehicle external loads

EXAMPLES Satellite buses and interstages

Structure
mechanical part(s) designed to carry internal and/or external loads or pressures, maintain stiffness, alignment, and/or stability, and provide support or containment for other systems or subsystems

NOTE The space vehicle structure is usually categorized into primary and secondary structure. Primary structure is defined as the part that carries the main flight loads and defines the natural frequencies and mode shapes. The secondary structure supports hardware items with negligible participation in the main vehicle load transfer, and the stiffness of secondary structure does not significantly influence the dynamic behavior of the vehicle.

System Threat Analysis Energy Level
the maximum energy level due to an impact resulting from a credible threat event determined in a system threat analysis

Ultimate Load
the maximum design load (force, stress, and/or strain) that the structure must withstand without rupture or collapse

Vibroacoustic
an environment induced by high-intensity acoustic noise associated with various segments of the flight profile. It manifests itself throughout the structure in the form of transmitted acoustic excitation and as structure-borne random vibration

Visual Damage Threshold (VDT)
an impact energy level shown by test(s) to create an indication that is barely detectable by a trained inspector using an unaided visual inspection technique

Yield Load
the maximum design load (force, stress, and/or strain) the structure must withstand without detrimental deformation

5 General Requirements

This section contains the mission requirements and general requirements for the design, material selection and characterization, fabrication and process control, quality assurance, repair and refurbishment, storage, and transportation for all structural items.

5.1 Mission Requirements

5.1.1 Loads and Pressure

Anticipated loads and pressures throughout the service life of a structural item shall be used to define the load/pressure spectra for design, analysis, and testing. Updates to the design spectra shall be evaluated to verify positive margins prior to flight.

5.1.1.1 Loads

All relevant structural load events experienced throughout the service life of a structural item shall be identified and considered. Load definitions shall include the load levels and durations during service life. Typical loading conditions relevant to the pre-launch, launch, and ascent phases include transportation, ground operations, operational pressures, engine ignition, thrust, aerodynamic loads, heat flux, pyrotechnic shock, maneuvering, and separation. Loading conditions for the on-orbit phase shall include operational loads and pressures, thrust, pyrotechnic and deployment shock, temperature, vibration, and micrometeoroid and debris impact. Loading relevant to reentry, descent, and landing shall include aerodynamic loads, temperatures, deployment, landing (including contingency), and post-landing heat soak.

5.1.1.1.1 Ground Handling, Transportation, and Post Landing Loads

As appropriate, the structural item shall be instrumented during ground handling and transportation to ensure that critical design loads and thermal and humidity levels are not exceeded. Loading conditions for all logistic, ground handling, and post-landing operations shall be developed and considered in designing the structural item.

5.1.1.1.2 Flight and Orbital Loads

The principal source of design loads for the structural item is the loads generated by the quasi-static and transient phenomena occurring during the various operational phases of launch, flight, and orbit (such as docking and EVA-related loads, where applicable). All loads shall be considered in the combinations that yield the specified statistical basis.

Loads in the low frequency regime shall be determined by analysis utilizing simulations and coupled system flexible body structural dynamic models, as appropriate for the event and the nature of the applied external environment. Other significant low frequency loads may occur due to on-orbit operations, such as appendage deployment, vehicle slewing, and mechanism operation.

The frequency range for loads analyses, typically up to 70 Hz, shall be supplied by the launch vehicle organization as determined by the resolution and fidelity of the launch vehicle models and forcing functions. The payload dynamic model shall have sufficient fidelity to capture the dynamic behavior of the payload in this frequency range.

5.1.1.2 Pressure

All pressure vessels, pressurized structures, and other pressure components shall withstand limit pressure applied simultaneously with other limit loads without experiencing detrimental deformation. They shall withstand ultimate pressure applied simultaneously with relevant ultimate loads without failure in the critical environment.

Pressure vessels and pressurized structures shall be able to withstand ultimate external pressures (destabilizing) and other loads without collapse or rupture when internally pressurized to the minimum anticipated operating pressure.

Provisions shall be made for venting, as required, to preclude damage due to over-pressurization of the launch vehicle and spacecraft during service life.

5.1.2 Environments

5.1.2.1 Thermal Environment

Effects of steady-state and transient extreme thermal conditions shall be considered in the structural design. Thermal effects on the structural item, including heat transfer rates, temperature levels and cycles, thermal stresses and deformations, and mechanical and physical property changes, shall be based on critical design and test thermal environments. Thermal effects due to contingency operations shall be considered.

5.1.2.2 Vibroacoustic Environment

Combined effects of the mechanically-induced transient and random vibration environments and acoustic environment shall be accounted for by analysis of the dynamic response to the environment.

5.1.2.3 Pyrotechnic Shock Environment

Shock loads induced by pyrotechnic shock events shall be considered, when appropriate.

5.1.2.4 Meteoroid and Orbital Debris Environment

The effect of the meteoroid and orbital debris environment shall be considered in designing the structures, including shielding, where required.

5.1.2.5 Space Flight Environments

The material degradation effects of atomic oxygen, ionizing radiation, solar ultraviolet, or plasma or spacecraft charging effects shall be considered in designing the structures, where required.

5.1.3 Life

All structural items shall be designed to withstand applied loads due to the natural and induced environments to which they are exposed during the service life and be able to fulfill mission objectives for the specified duration in operation.

The service life of a structural item shall comprise all ground operations such as transportation, handling, testing, and storage, as well as all phases of pre-launch, launch, operation and descent.

The phases and applicable loads and durations shall be determined based on

a) requirements of service life (i.e., single mission, expendable, reusable, or long-term deployment),

b) the effect of all degradation mechanisms upon materials used in construction (i.e., both terrestrial and space environments and all loading regimes to be experienced), and

c) experience with similar structural items.

5.2 Design Requirements

5.2.1 Static Strength

All structural items shall possess adequate strength to preclude detrimental deformation at the corresponding loads and pressures in the expected test and operating environments throughout their respective service lives. They shall also possess adequate strength to preclude catastrophic failure at design ultimate load and pressure, and operating environments.

The design of composite structures shall consider configurations where fiber fracture is the primary mode of failure. Failure of joints and transitions requiring complex interaction of various failure modes, such as in-plane shear, interlaminar shear and tension, and fiber failure shall be avoided, if possible.

5.2.2 Margin of Safety

Margin of safety (MS) is a measure of a structure's predicted reserve strength in excess of the design criteria. The MS of every structural item shall be positive under combined loads, pressures, and accompanying environments for each design condition specified in Sections 5.1.1 and 5.1.2. Additional requirements for special structures that have published standards are provided in Section 7.1. The MS shall be determined using material allowables with appropriate statistical bases. Minimum design safety factors used in MS calculations for structures are listed in Table 1. These factors, which are based on industry common practice, shall apply to the design of expendable and reusable structural items for the initial mission. MS calculations for reusable structural items shall consider degradation of material properties, if any, after being subjected to the service life. Additional design factors for the following special situations shall be established based on prior experience or test data:

a) personnel safety when the structural item contains stored energy;

b) highly localized stresses at locations such as holes, corners, or fillets;

c) stresses in complex joints and fittings.

5.2.3 Buckling Strength

Buckling shall not cause structural failure when ultimate loads are applied, nor shall buckling deformations from limit loads degrade functioning of any system or produce changes in the loading that are not accounted for. All structural items subjected to significant in-plane stresses (compression and/or shear) under any combination of ground loads, flight loads, or loads resulting from temperature changes shall be analyzed or tested for buckling failure. Buckling evaluation shall address general instability, local or panel instability, crippling, and creep. Design loads for buckling shall be ultimate loads, except that the minimum anticipated value shall be used for any load component that tends to alleviate buckling.

5.2.4 Static Stiffness

All structural items shall possess adequate stiffness to preclude detrimental deformation due to loads corresponding to the expected test and operating environments throughout their respective service-lives. They shall also possess adequate stiffness to preclude collapse at design ultimate load. The cumulative elastic, permanent, and thermal deformations shall not degrade structural capability or adversely affect aerodynamic characteristics.

Table 1 — Minimum Design Factors of Safety

Design and Test Strategy	Design Factor of Safety on Limit Loads			Typical Application
	Yield[a]	Ultimate		
		Unmanned	Manned	
Qualification test dedicated unit(s) to ultimate	1.10	1.25	1.40	Fleet
Protoqualification test single flight unit	1.25	1.40	1.40	Small Fleet
Proof test all flight units	1.10	1.25[a]/1.40[b]	1.40	Few
No qualification or protoqualification test[c]	1.60	2.00	2.25	One-of-a kind, or modification to existing structure

a Applies to metallic structural items only

b Applies to nonmetallic structural items only

c Applies to metallic and secondary nonmetallic structural items

5.2.5 Dynamic Behavior

Spacecraft shall be designed to avoid coupling with the launch vehicle control system. The structural items' stiffness shall be consistent with the minimum required stiffness to ensure structural adequacy under transient dynamic loads, and the body-bending frequencies shall be within the limits imposed by the vehicle flight control system.

The spacecraft shall be designed to avoid load-inducing dynamic coupling of flexible modes during launch, on-orbit operations, and landing. When avoiding such coupling is not practical, careful evaluation of the resulting dynamic loads, and their simulation by analysis or test, shall be required.

Structures shall be capable of performance within specification after exposure to vibroacoustic and shock environments.

5.2.6 Dimensional Stability

Structural materials shall remain dimensionally stable under given environments during ground, flight, landing, and post-landing operations. The structural item shall not lose alignment that would impact the mission under the action of applied loads, including the effects of temperature, humidity, and venting.

5.2.7 Fatigue Life

All non-fracture-critical structural items shall have adequate fatigue life in order to achieve mission success. Unless otherwise specified, fatigue life shall be at least 4 times service life with no assumed initial damage or defects.

5.2.8 Damage Tolerance (Safe Life)

All fracture-critical structural items shall be damage tolerant, i.e., have adequate safe life. For metallic structural items, it is required that the largest undetected crack (consistent in size with the proof test limits or sensitivity of the applied NDE) that could exist in the fracture-critical items will not grow to failure when subjected to cyclic and sustained loads in a specified number of service lifetimes. For composite structural items, except composite overwrapped pressure vessels (COPV), the broader range of flaws must be considered. Loads to be considered include testing, launch and/or landing, and normal operational cycles and durations encountered in service. Unless otherwise specified, the required safe life is at least 4 times service life. For structural items of a reusable launch vehicle, and multi-mission spacecraft or payloads which have scheduled inspection intervals, the required safe life is at least 4 times the inspection interval. Detailed damage tolerance requirements shall be specified by the procuring authority. NASA-STD-5007 or ISO 21347 may be used if appropriate for the specific application. For pressure vessels and other pressurized hardware, damage tolerance requirements set forth in ANSI/AIAA S-080 and S-081 shall be met.

5.2.9 Impact Damage Tolerance

The residual strength of composite structural items after impact shall not be degraded below a predetermined level, as specified by the procuring authority for the specific application. For COPVs, the residual strength shall not be degraded below their ultimate load requirements after being subjected to the lesser of a system threat analysis energy level or visual damage threshold (VDT) level impact. Detailed impact damage tolerance requirements shall be specified by the procuring authority. NASA-STD-5007 or ISO 21347 may be used if appropriate for the specific application. For COPVs, impact damage tolerance requirements set forth in ANSI/AIAA S-081 shall be met.

5.2.10 Stress-Rupture Life

Composite and other nonmetallic structural items shall be designed to meet the service life requirement considering the time they are under sustained load. There shall be no credible stress-rupture failure modes based on stress-rupture data for a specified probability of survival. Unless otherwise specified, the minimum probability of survival associated with catastrophic failure shall be 0.999.

5.2.11 Corrosion and Stress-Corrosion Cracking Control

Effect of the following factors on material properties over the service life of the structural item shall be considered:

a) corrosive or incompatible environments;

b) galvanic corrosion;

c) stress-corrosion cracking.

5.2.12 Outgassing

The selection of structural materials and processes shall consider the effects of outgassing on the structural items and the surrounding elements or systems.

5.2.13 Meteoroid and Orbital Debris Protection

When required, the space vehicle primary structures, pressurized components, thermal radiators, battery cells, and electronic boxes, etc., shall be protected from meteoroid and orbital debris (M/OD) impact in order to prevent risk of catastrophic failure. The selection and design of material and M/OD protection systems shall be based on a defined probability of survival, which may be influenced by the probability of impact, critical M/OD size, and material response to hypervelocity impacts. The magnitude and characteristics of M/OD flux, as well as methods of calculating the probability of penetration, shall be determined in accordance with the requirements specified by government or industry standard. Furthermore, the space vehicle structural item shall be designed in a manner that complies with international guidelines that are in place to limit the amount of debris generated should the item disintegrate during its mission (for example, NASA-STD-1740.14).

5.3 Material Requirements

5.3.1 Metallic Materials

5.3.1.1 Metallic Material Selection

Material selection for metallic structures shall be based on well-documented material strengths, physical properties, and fatigue/fracture characteristics consistent with overall system requirements.

5.3.1.2 Metallic Material Evaluation

Selected metals shall be evaluated for material processing, fabrication methods, manufacturing operations, refurbishment procedures and processes, and other factors that affect the resulting strength and fatigue/fracture properties of the material in the fabricated and refurbished configurations.

Metals susceptible to stress-corrosion cracking or mechanisms such as hydrogen embrittlement shall be evaluated by performing sustained load fracture tests when applicable data are not available.

5.3.1.3 Metallic Material Characterization

Allowable mechanical properties of all metals selected for structural items shall be characterized in sufficient detail to permit reliable and high-confidence predictions of their structural performance in the expected operating environments, unless these properties are available from reliable sources such as MMPDS-01, MCIC-HB-01, Aerospace Structural Metals Handbook, and other sources.

Where material properties are not available, they shall be characterized by tests. Uniform test procedures shall be used to determine material strength and fracture properties as required. These procedures shall conform to recognized standards such as ASTM E-8 and E-9, E-399 and E-647, and E-740, developed by the American Society for Testing and Materials (ASTM). Test specimens and procedures utilized shall provide valid test data for the intended application. Sufficient tests shall be conducted so that meaningful nominal values of fracture toughness, fatigue data, and crack growth rate data, corresponding to each alloy system, temper, product form, thermal and chemical environments, and loading spectra, can be established to evaluate compliance with strength, safe life, and/or fatigue requirements.

5.3.1.4 Metallic Material Strength Allowables

For all primary metallic structures that are not fail safe, A-basis strength values shall be used for margin of safety calculations. At a minimum, B-basis values shall be used for fail safe or secondary structures. In special circumstances where design data at the required statistical level are not established, limited data acquisition tests to establish S-basis allowables, as defined in MMPDS-01, may be conducted. For fracture-critical items, the calculation shall be based on the material's A-basis allowable.

5.3.2 Composite Materials

5.3.2.1 Composite Material Selection

At a minimum, composite materials used for fabricating structural items shall be selected on the basis of environmental compatibility, material strength and modulus, and stress-rupture properties. The effects of fabrication process, temperature and humidity, load spectra, and other conditions, which may affect strength and stiffness of the material in the fabricated configuration, shall be included in the rationale for selecting the composite materials.

5.3.2.2 Composite Material Evaluation

Materials selected for a composite structure shall be evaluated with respect to the material processing, fabrication methods, manufacturing operations and processes, operating environments, service life, and other pertinent factors that affect resulting strength and stiffness properties of the material in the fabricated configurations.

5.3.2.3 Composite Material Characterization

Strength and other mechanical properties of composite materials shall be sufficiently characterized for all critical failure modes and expected environmental conditions unless these properties are available from reliable sources such as MIL-HDBK-17, the DOD/NASA Advanced Composites Design Guide, and other sources.

Test methods using samples representative of the geometry, layup, and manufacturing processes involved in hardware fabrication shall be used to determine material properties as required. The anisotropy of laminated composite structural elements shall be accounted for when establishing material properties and failure modes. Test specimens and procedures shall follow standardized test methods whenever available in order to provide valid test data for the intended application.

5.3.2.4 Composite Material Strength Allowables

Strength allowables for composite materials shall be determined from testing of coupons, or sub-scale or full-scale composite parts. When sub-scale and coupon data are used in the database, correlation between coupon/sub-scale data and full-scale data shall be established.

A-basis allowables shall be used for non-fail-safe primary and/or fracture-critical composite structures. For fail-safe primary structures and all secondary structures, B-basis allowables shall be used as a minimum. For secondary structures only, S-basis allowables may be used with the approval of the procuring authority.

Design development tests shall be conducted to evaluate materials and joint behavior. The tests may range in complexity from coupon tests and sub-scale tests to full-scale structures.

Design allowables shall be established for each anticipated failure mode using coupons or test specimens taken from a part fabricated using the same process and similar geometry as the full-scale structure. The tests shall develop relationships between strength/temperature and strength/moisture for the entire range of storage, transportation, and operational environments for each critical area of the structure. A series of test specimens of increasing complexity from coupons, sub-scale, to full-scale shall be used to establish allowables for full-scale structures.

5.3.3 Glass and Ceramic Materials

5.3.3.1 Glass and Ceramic Material Selection

Material selection for glass or ceramic structures shall be based on well-documented material properties appropriate for the intended application. Key characteristics to be considered shall include fracture toughness, hardness, Weibull parameters, dimensional tolerances, environmental compatibility, elastic properties, thermal properties, electrical properties, surface finish, and surface quality (presence of surface defects caused by impurities). For each type of glass or ceramic component, temperature and stress distributions shall be determined for steady-state and transient operating conditions. These data shall then be used in conjunction with accepted life prediction programs to make initial assessments of the probability of survival of the component over its intended lifetime. The minimum acceptable probability of survival shall be set on the basis of mission requirements.

5.3.3.2 Glass and Ceramic Material Evaluation

Selected glass or ceramics materials shall be evaluated with respect to material processing, manufacturing robustness, inspection protocols, refurbishment procedures and processes, and other factors that affect the functional performance of the material in fabricated and refurbished configurations. Materials, which are susceptible to time-dependent or (temperature or stress) cycle-dependent failure, shall be evaluated by performing stress-rupture and/or cyclic fatigue tests when applicable data are not available.

5.3.3.3 Glass/Ceramic Material Characterization

Mechanical and thermal properties of all glass or ceramic materials selected for structural items shall be characterized in sufficient detail to permit reliable and high-confidence predictions of operating stresses and temperatures for steady-state and transient conditions. The Weibull and slow crack growth/cyclic fatigue parameters required to predict probability of survival also must be characterized. Potential sources of these data include material suppliers, technical publications, and established databases.

Where material properties are not available, they shall be characterized by established tests. When possible, these procedures shall conform to recognized standards, such as standard test methods developed by the ASTM. If no standards exist, adopted test procedures must be based on the best available methods as defined in the current technical literature. Sufficient tests shall be conducted so that statistically meaningful data corresponding to each material type, manufacturing method, product form and size, thermal and chemical environments, and operating spectra can be established to evaluate compliance with strength, safe-life, and/or fatigue requirements.

5.3.3.4 Glass and Ceramic Material Strength Allowables

Strength allowables for glass and ceramics shall be selected on a statistical basis. The allowables to be used with the predicted design limit stresses shall be such that the probability of failure of the structural item is consistent with the reliability requirements set by the procuring authority. In the absence of an allocated reliability to the structural item, the probability of failure shall not be greater than 1×10^{-6}.

5.3.4 Polymeric Materials

5.3.4.1 Polymeric Material Selection

Adhesives and other polymeric materials used for a structural item shall be selected on the basis of environmental compatibility, material strength and modulus, fatigue, creep deformation and relaxation, and stress-rupture properties as dictated by the application. Effects of fabrication processes, temperature and humidity, load spectra, and other conditions that may affect strength, stiffness, and dimensional tolerance of the material in the fabricated configuration shall also be included in the rationale for selecting polymeric materials. Other material selection considerations shall include flammability, toxicity, and outgassing.

5.3.4.2 Polymeric Material Evaluation

Materials selected for a polymeric structural item shall be evaluated with respect to the material processing, manufacturing operations and processes, operating environments, service life, and other pertinent factors that affect resulting strength, stiffness, and dimensional tolerance properties of material in fabricated configurations.

5.3.4.3 Polymeric Material Characterization

Properties of the polymeric materials selected shall be characterized in their expected configurations and operating environments. Test methods using samples representative of manufacturing processes involved in structural hardware fabrication shall be used to determine material properties as required. Test specimens and procedures shall follow standardized test methods (such as those published by ASTM) whenever available in order to provide valid test data for the intended application.

5.3.4.4 Polymeric Material Strength Allowables

Strength allowables for polymeric materials shall be determined from testing of coupons, sub-scale, or full-scale parts. When sub-scale and coupon data are used in the database, correlation between coupon/sub-scale data and full-scale data shall be established.

The bases for design allowables for primary and secondary structural components shall correspond to A-basis and B-basis values, respectively. For fail-safe primary structural components, the B-basis allowables may be used. In special circumstances where design data at the required statistical level are not established, special limited data acquisition tests to establish S-basis allowables may be conducted.

5.4 Fabrication and Process Control

Design of structural items shall use well-characterized fabrication processes and procedures. The fabrication processes of each structural item shall be controlled and documented and all such fabrication processes and operators shall have all required certifications. Proven processes and procedures for fabrication and repair shall be used to preclude damage or material degradation during material processing and manufacturing operations. In particular, special attention shall be given to ascertain that the thermal treatment, machining, drilling, grinding, and other operations are within the state of the art and appropriate for the application.

For fracture-critical structures, fracture toughness, fatigue crack growth rate, mechanical, and physical properties shall be within established design limits after exposure to the intended fabrication processes. Fracture control requirements and procedures shall be defined in applicable drawings and process specifications. Detailed fabrication instructions and controls shall be developed and used to ensure proper implementation of fracture control requirements.

For composite structures, coupon tests and manufacturing process checks shall be performed to show that the as-built flight articles satisfy design and analysis assumptions and are representative of the verification test articles.

Materials shall have certifications that demonstrate acceptable variability in material properties to ensure repeatable and reliable performance. The fabrication processes shall control or eliminate detrimental conditions in the fabricated article.

An inspection plan shall be developed to identify all key process parameters (KPP) essential for verification. In-process inspection or process monitoring shall be used to verify the setup and acceptability of critical parameters during the fabrication process/procedure.

5.5 Quality Assurance

A quality assurance or inspection program based on comprehensive study of the product and engineering requirements shall be established in accordance with Sections 5.5.1 and 5.5.2 to ensure that necessary NDE and acceptance proof tests are performed effectively. The program shall ensure that no damage or degradation occurred during material processing, fabrication, inspection, acceptance tests, shipping, storage, assembly, and operational use and refurbishment, and that defects that could cause failure are detected or evaluated and corrected. Quality assurance data for all structural items shall be maintained throughout the service life. As a minimum, the following shall be included in the quality assurance program.

5.5.1 Inspection

5.5.1.1 Inspection Plans

An inspection master plan shall be established before fabrication begins. The plans shall specify appropriate inspection points, and inspection techniques for use throughout the program, beginning with material procurement and continuing through fabrication, assembly, acceptance proof test, shipment, assembly, and operation as appropriate. In establishing inspection points and inspection techniques, emphasis shall be placed on verification of key analysis parameters. Consideration shall be given to the material characteristics, fabrication processes, design concepts, presence of corrosion such as pitting and crevice cracking, and accessibility for inspection of defects.

5.5.1.2 Inspection Techniques

For fracture-critical metallic structural items, selected inspection techniques shall be able to determine the size, geometry, location, and orientation of a crack or a crack-like defect. Inspection techniques, such as dye penetrant, magnetic particle, eddy current, radiography, and ultrasound, shall be used to detect cracks as appropriate. NDE techniques used shall have a demonstrated 90% probability of detection at a 95% confidence level.

Inspection techniques for composite materials shall include visual inspection performed in conjunction with appropriate state-of-the-art NDE techniques. Inspections shall be performed to look for flaws such as nonuniform or broken fibers, delaminations, fiber wrinkles and waviness, dry fibers (i.e., fuzzing or "brooming"), machining damage, impact damage, and uniformity of surface coatings, if applicable. When required, inspections shall be augmented by use of optical magnification or solvent wipe techniques (i.e., for detection of cracks or delaminations). Proven NDE techniques, such as ultrasound, radiography, thermography, computed tomography , and shearography, shall be used to identify and characterize critical defects as appropriate. The appropriateness and ability of the NDE methods selected to detect and characterize critical defects shall be established. NDE shall be performed in accordance with applicable published industry or government standards.

5.5.1.3 Teardown Inspection

For structural items in reusable launch vehicles or multi-mission payloads, a teardown inspection shall be performed as appropriate when damage tolerance demonstration is based on the inspection interval.

5.5.1.4 Inspection Data

Inspection data for the structural items shall be maintained throughout service life. These data shall be periodically reviewed and assessed to evaluate trends and anomalies associated with the inspection procedures, equipment and personnel, material characteristics, fabrication processes, design concept, and structural configuration. The result of this assessment shall form the basis of any required corrective action.

5.5.2 Acceptance Proof Test

All fiber-reinforced composite and bonded primary structures shall be proof tested. When the proof tests are conducted at temperature and humidity conditions other than the worst-case design environment, the change in material properties at the test conditions shall be accounted for in the test. The test configuration shall simulate structural interfaces in order to replicate launch and flight external load distributions.

5.5.3 Traceability

Traceability shall be maintained on all fracture-critical structural items throughout their development, manufacturing, testing, and service. As a minimum, serialization shall be required on all fracture-critical items and they shall have traceability to material heat treat lot or composite manufacture and cure lot. A log shall be maintained for each fracture-critical item to record all significant manufacturing assembly processes, load cycles, inspections, and tests occurring during the time period from fabrication to the end of service life. Engineering drawings for fracture-critical items shall contain notes that label the hardware item as "fracture critical" and specify the appropriate inspections or flaw screening methods to be used.

5.6 Repair and Refurbishment

When inspections reveal structural damage or defects exceeding permissible levels, nonconforming hardware shall be assessed by a material review board. All repairs and refurbishments shall use an approved repair process. All repaired or refurbished hardware shall be re-verified after each repair or refurbishment by the applicable test procedure for new hardware to verify structural integrity and establish suitability for continued service.

5.7 Storage

When structural items are stored, they shall be protected against exposure to adverse environments (e.g., temperature, humidity, etc.). In addition, they shall be protected against damage (e.g., abrasion, cutting, impact, etc.). Critical environmental conditions shall be recorded.

5.8 Transportation

When structural items are transported, they shall be packaged in a manner that will provide protection against damage from physical or environmental sources. These sources include, but are not limited to, exposure to adverse environmental conditions (e.g., temperature extremes, humidity, water, prolonged exposure to sunlight, etc.), physical impact, vibration, and shock during transport.

Critical environmental and transportation conditions that pose a threat to the integrity of the structural item such as temperature extremes, excessive vibration, or shock loading shall be recorded. The nature of recording (i.e., continuous vs. maximum) and parameters to be monitored shall be commensurate with the threat assessment for the method of transportation and the consequences of these transportation parameters on the structural item. As a minimum, records documenting transportation events, packaging used, method of conveyance, person or company responsible for transport, dates of shipment and receipt, and a written report including photographs of visual inspection results of the package and its contents shall be kept. Any adverse events or observations shall be recorded and assessed for implications about the integrity of the structural item.

6 General Requirements Verification

6.1 Design Requirements Verification

Verification methods appropriate to establish compliance with the design requirements specified in Section 5.2 are shown in Table 2 and discussed in the following sections.

Table 2 — Design Requirements Verification Matrix

Requirement Section	Section Title	Verification Method	Verification Section
5.2.1	Static Strength	Analysis & Test	6.1.1
5.2.2	Margin of Safety	Analysis or Test	6.1.2
5.2.3	Buckling	Analysis or Test	6.1.3
5.2.4	Static Stiffness	Analysis or Test	6.1.4
5.2.5	Dynamic Behavior	Analysis & Test	6.1.5
5.2.6	Dimensional Stability	Analysis or Test	6.1.6
5.2.7	Fatigue Life	Analysis or Test	6.1.7
5.2.8	Damage Tolerance (Safe Life)	Analysis or Test	6.1.8
5.2.9	Impact Damage Tolerance	Test	6.1.9
5.2.10	Stress-Rupture Life	Analysis or Test	6.1.10
5.2.11	Corrosion and Stress-Corrosion Cracking Control	Analysis	6.1.11
5.2.12	Outgassing	Analysis or Test	6.1.12
5.2.13	Meteoroid and Orbital Debris Protection	Analysis or Test	6.1.13

6.1.1 Static Strength Verification

Static strength of a specific structural item shall be verified by structural analysis and tests, considering environments such as mechanical loads, pressure, and temperature soak and gradients. Verification may be performed by analysis only, if the conditions defined in Section 6.1.1.3 are met.

6.1.1.1 Structural (Stress) Analysis

Structural analysis shall be performed for all loads and environments in Sections 5.1.1 and 5.1.2 to determine critical internal loads (forces, stresses, and/or strains). As appropriate, effects of deformations, temperatures, and geometric nonlinearities shall be included in calculating internal loads. Structural analysis for flight conditions shall be performed based on test-correlated analytical models.

Analysis of laminated composite structures shall address ply-by-ply stress (strain) response to applied loads and environments to determine minimum margins of safety for each applicable failure mode such as fiber fracture, in-plane shear failure, and delaminations.

Analysis shall demonstrate positive margins of safety for all structures for both yield and ultimate loads. The most severe combination of thermal, mechanical, and pressure loads occurring at the same instant in time shall be used in a rational manner according to the following equation.

$$K_1L_{\text{mechanical}} + K_2L_{\text{thermal}} + K_3L_{\text{pressure}} = \text{Total (Yield or Ultimate) Load,}$$

and

$$MS = [\text{Allowable (Yield or Ultimate) Load/Total (Yield or Ultimate) Load}] - 1$$

where:

K_i = design factor of safety on yield or ultimate from Table 1 or Table 4, as applicable, when term is additive to the algebraic sum, $\sum L$

K_i = 1.0 when term is subtractive to the algebraic sum, $\sum L$

$L_{mechanical}$ = internal loads (forces, stresses, and/or strains) due to externally applied mechanical limit loads; e.g., inertial loads, aerodynamic pressure

$L_{thermal}$ = internal loads (forces, stresses, and/or strains) due to thermally-induced loads at the maximum and minimum predicted temperatures including modeling uncertainty margins

$L_{pressure}$ = internal loads (forces, stresses, and/or strains) due to design limit pressures

6.1.1.2 Load and Pressure Test

Test results of the qualification tests specified in Section 6.3 shall be used to verify strength requirements.

6.1.1.3 Static Strength Verification by Analysis Only

Static strength of a specific structural item may be verified by analysis only if the following conditions are met and approval is granted by the procuring authority.

a) The item is metallic, or a secondary non-metallic structure.

b) The structural design is simple (e.g., statically determinate) with easily-determined load paths and well-defined failure modes, it has been thoroughly analyzed for all critical load conditions, and there is a high confidence in the magnitude of all significant loading events.

c) The structure is similar in overall configuration, design detail, and critical load conditions to a previous structure which was successfully test-verified, with good correlation of test results to analytical predictions.

d) Development and/or component tests have been successfully completed on critical, difficult to analyze elements of the structure. Good analytical model correlation to test results has been demonstrated.

6.1.2 Margin of Safety (MS) Determination

The MS shall be determined by analysis using the appropriate statistically-based material allowable. Test data shall be used to validate results when necessary. Selection of factors of safety in MS determination shall, as a minimum, be in accordance with Table 1. For combined mechanical, thermal, and pressure loads, the MS shall be calculated using the equation shown in Section 6.1.1.1.

6.1.3 Buckling Verification

6.1.3.1 Buckling Analysis

Evaluation of buckling strength shall consider the combined action of primary and secondary stresses and their effects on general stability, local or panel instability, crippling, and creep. Analysis shall include consideration of the relative deflection of adjoining structures. Defects and geometrical imperfections in the structures shall be adequately taken into account. The buckling strength shall be the predicted buckling load times an appropriate knockdown factor to account for unknown defects, geometrical imperfections, and the structural item’s configuration. Knockdown factors must be based on relevant test data or experience that provide a lower bound for the buckling strength.

6.1.3.2 Buckling Test

Representative structure shall be tested under the conditions cited in Section 5.2.3. As a minimum, development tests for primary structure shall be conducted simulating compressive and/or shear design loads when any of the following apply:

a) configurations are shells of complex shape;

b) coupling between various modes of failure is possible;

c) no theory or test correlation factor exists.

6.1.4 Static Stiffness Verification

6.1.4.1 Static Stiffness Analysis

Static stiffness analysis shall be performed to verify structural response to quasi-static loads. Analysis shall determine required displacements and internal forces under representative applied loads and boundary conditions.

6.1.4.2 Static Stiffness Test

When required, structural tests shall be conducted under maximum expected loads to determine structural stiffness and other responses including displacements and internal load distribution.

6.1.5 Dynamic Behavior Verification

6.1.5.1 Dynamic Analysis

Dynamic analysis shall be performed for various flight events such as lift-off, engine ignition, aerodynamics, maneuvering, staging, reentry, and landing. Structural dynamic mathematical models and associated load transformation matrices shall be developed to support the loads analysis. Models used in dynamic analyses shall represent structural assemblies by characterization of dynamic parameters (natural frequencies and mode shapes) and associated effective masses and damping. Dynamic models shall be updated to reflect changes in design and the loads environment as a program matures and more data from ground test and flight become available.

Low frequency (typically below 70 Hz) dynamic analysis shall be performed on an integrated spacecraft and launch vehicle model to verify frequency requirements and determine associated modal characteristics including natural frequencies and mode shapes.

Loads analysis shall provide structural accelerations, internal member loads and stresses, deflections and rotations, and interface forces at various components in sufficient detail to allow verification of structural integrity. The analysis shall provide acceleration, velocities, and displacements at specified locations to a probability level of 99.7% with 90% confidence, unless specified otherwise by the procuring authority.

Verification loads analysis shall be performed to provide final definition of loads using structural dynamic models and forcing functions verified by modal survey and other applicable tests. These analyses, including analysis methodologies, shall be verified by an independent organization when such requirements are specified by the procuring authority.

6.1.5.2 Vibration, Acoustic, and Shock Analysis

Vibroacoustic analysis and/or survey shall be performed by the launch vehicle organization using the launch vehicle environment to verify the acoustic spectrum and level in the payload bay/shroud or external spacecraft location.

Vibroacoustic loads analysis shall provide structural accelerations, internal member loads and stresses, deflections and rotations, and interface forces at various components in sufficient detail to allow verification of structural integrity.

Shock analysis shall be performed on all shock-inducing events, including pyrotechnic initiation and separation, to define environments at spacecraft locations where hardware sensitive to shock damage is located.

6.1.5.3 Mode Survey Test

Mode survey (also referred to as modal survey) tests of flight-quality structure shall be conducted to verify mathematical models of dynamically complex structures such as spacecraft, upper stages, and fairings. All significant equipment components shall have an accurate dynamic representation in the test. All significant modes of vibration, mode shapes, frequencies, and associated damping over the frequency range of interest for loads analyses (typically up to 70 Hz, unless specified otherwise by the launch vehicle contractor) shall be measured. Modal correlation requirements shall be specified by the procuring authority. NASA-STD-5002 or Aerospace TOR-2003 (8583) 2886 may be used if appropriate for the specific application. Mode survey test results shall be certified by an independent organization that validates analytical models, when required by the procuring authority.

6.1.5.4 Vibration, Acoustic, and Shock Tests

Vibration, acoustic and shock tests shall be conducted in accordance with the requirements of MIL-STD-1540 or as specified by the procuring authority.

6.1.6 Dimensional Stability Verification

As appropriate, dimensional stability shall be verified by material testing to determine changes in structural dimensions and material properties due to environment influences such as moisture release and absorption, aging, and creep.

6.1.7 Fatigue-Life Verification

As appropriate, fatigue life shall be verified for non-fracture-critical structural items by fatigue analysis or test. Fracture mechanics-based damage tolerance (safe life) analysis or test may be used as a substitute for fatigue analysis or test.

6.1.7.1 Fatigue Analysis

When a fatigue analysis is used to verify the fatigue life of a structural item, nominal values of fatigue characteristics, including fatigue stress-life data (S-N) and/or fatigue strain-life (ε-N) data of the material shall be used. These data shall be taken from reliable sources such as MMPDS-01 and the Aerospace Structural Metal Handbook. Analysis shall account for the spectra of expected operating loads and environments. Miner's Rule ($\Sigma n/N$) is an acceptable method for predicting the effects of variable amplitude fatigue cyclic loading.

6.1.7.2 Fatigue Test

Testing of specimens in a representative environment to demonstrate fatigue life of a specific part, together with stress analysis, is an acceptable alternative to analytical prediction. The number of tests must be sufficient to form a statistically meaningful database.

6.1.8 Damage Tolerance (Safe Life) Verification

6.1.8.1 Damage Tolerance (Safe Life) Analysis

For all metallic, glass, and ceramic fracture-critical parts, damage tolerance analysis (also referred to as safe-life fracture mechanics analysis) shall be performed to verify that the parts meet the damage tolerance (safe life) requirements specified in Section 5.2.8. Undetected crack(s) shall be assumed to be in critical location(s) and in the most unfavorable orientation(s) with respect to the applied stress and material properties. The size of the crack(s) shall be based on crack-screening proof test-limits or the detection capability of appropriate NDE technique(s) used in the acceptance tests. Nominal values of fracture toughness and fatigue crack growth rate (da/dN) data shall be used in the analysis.

6.1.8.2 Damage Tolerance (Safe Life) Test

Damage tolerance verification for fracture-critical metallic, glass, and ceramic parts may be performed by testing flight-quality parts with pre-fabricated crack(s) of controlled size(s) in a representative environment. Coupons may be allowed in lieu of full-scale, flight-quality articles only for metallic parts when the stress field is well defined and the material properties are representative of the flight parts. The size and shape of crack(s) must correspond to the detection capability of the NDE to be imposed on the flight parts.

Damage tolerance verification for fracture-critical composite parts shall be performed by test only. The test spectrum shall adequately represent all cycles, time, and environments associated with part history. Proven accelerated test techniques may be used. Damage tolerance test(s) for fracture-critical composite parts shall be performed by using full-scale, flight-quality articles, with pre-fabricated flaw(s). The size of the flaws must be based on the detection capability of the NDE to be imposed on the flight parts.

For components where neither damage tolerance analysis nor damage tolerance testing are appropriate, such as for some composite material failure modes, proof testing of each flight hardware item may be used to establish confidence in a part's damage tolerance, provided it is approved by the procuring authority.

6.1.9 Impact Damage Tolerance Verification

Testing in a representative environment is the only acceptable method to demonstrate impact damage tolerance of fracture-critical composite parts. Impact damage tolerance is verified when it is shown that residual strength does not degrade below the predetermined level. Full-scale articles, which are representative of the flight part, with induced impact damage shall be used as the test specimens. For COPVs, either system threat analysis energy levels or verified VDT energy levels, whichever is less, shall be used to determine the impact energy level in the impact damage tolerance tests.

6.1.10 Stress-Rupture Life Verification

Stress-rupture life for composite structural items shall be verified by analysis supported by test data.

6.1.11 Corrosion and Stress-Corrosion Cracking Control Verification

A corrosion control plan shall be developed for structural items that are prone to stress-corrosion cracking or corrosion due to environmental or galvanic effects. The corrosion control plan shall be reviewed for adequacy and tracked for effectiveness.

6.1.12 Outgassing Verification

Outgassing levels of structural materials for the specified operating conditions shall be shown by analysis, test, or documented engineering practice to be less than the specified allowable. The effects of outgassing on material properties, dimensional characteristics, and residual stresses shall be established and included in the determination of material properties, analytical evaluations, and/or experimental validations for all structural items.

6.1.13 Meteoroid and Orbital Debris Shielding Verification

When required by the procuring authority, mission-critical components that are vulnerable to M/OD impacts should be tested for M/OD damage at representative velocity levels.

6.2 Acceptance Tests

6.2.1 Nondestructive Inspection (NDI)

Each structural item shall be subjected to NDI if required by the inspection plan of Section 5.5.1. NDI can be conducted either at the component level, or at the assembly level for some structural items.

6.2.2 Proof Load and Pressure Tests

Composite and bonded primary structures shall be subjected to an acceptance proof test at a minimum level of 1.1 times the limit load. During acceptance proof testing, the test item shall not rupture, experience severe damage, or exceed specifications on linear and/or nonlinear deformation. If necessary, the proof-test parameters, such as load, pressure, and temperature, shall be suitably adjusted to account for the environmental effects on material properties and stress fields in order to make the proof test representative of the critical condition. Structural items made of other materials shall be proof tested as required.

In exceptional cases where such acceptance testing is not practical, deviation may be granted by the procuring authority, provided the manufacturer of the composite/bonded structural item demonstrates that:

a) certified and controlled specifications are used,

b) personnel are properly trained and certified,

c) mechanical properties of each component are verified by tag end tests, and

d) NDE is adequate to validate the quality and integrity of the hardware.

6.2.3 Vibration and Shock Tests

Vibration and shock tests on structural items shall be conducted in accordance with the requirements specified by the procuring authority.

6.3 Qualification Program

Every structural item (new design or redesign) shall be verified by a qualification program in accordance with the test options shown in Table 3. Qualification tests shall be conducted on a flight-quality structural item all of whose parts have been subjected to NDI and an acceptance proof test as described in Section 6.2. Tests can be conducted either at the component level, assembly level, or at a higher level of integration. The following tests shall be conducted on all new or substantially modified structural items as appropriate:

a) inspection;

b) proof load and pressure tests;

c) vibration and shock tests;

d) ultimate load and burst tests.

A fatigue life and/or damage tolerance test may also be a part of the qualification test program, if required. In general, a damage tolerance test shall be conducted on a separate test article. However, it may be conducted on the qualification test article whenever feasible.

Table 3 — Minimum Qualification Test Factors

Test Options	Test Factor on Limit Loads		Test Success Criteria
	Unmanned	Manned	
Ultimate load test on dedicated unit	1.25	1.40	No failure at ultimate test level; No detrimental deformation or damage at 1.1 x limit load
Protoqualification test single flight unit	1.25	1.25	No detrimental deformation or damage
Proof test all flight units	1.10	1.10	No detrimental deformation or damage

6.3.1 Proof Load and Pressure Tests

The qualification test article shall be subjected to proof load and pressure tests if required per Section 6.2.2.

6.3.2 Vibration and Shock Tests

A structural item shall undergo appropriate acceptance- and qualification-level vibration and shock test(s) as required per requirements specified by the procuring authority.

6.3.3 Inspection

Inspections of the qualification test article shall be performed per the requirements of Section 5.5.1 to ensure that the qualification hardware conforms to applicable drawings and specifications for functional performance.

6.3.4 Qualification Load and Pressure Tests

A qualification load test shall be conducted on a flight-quality article to verify compliance with the design qualification factor of safety requirement established for each type of structural item. The qualification load test parameters such as load and temperature shall be suitably adjusted to account for environmental effects on material properties and stress fields in order to make the test representative of the lowest margin condition.

The test article shall be held at the qualification load level for at least the period required by the procuring authority. The test article shall not exhibit catastrophic failure at or prior to the end of the hold time.

For composite/bonded structures, to account for degradation of material properties due to combined temperature and moisture effects, one of the following test approaches shall be used.

a) Perform the qualification test on the test article which has been environmentally preconditioned under the worst-case combination of temperature and moisture conditions.

b) Perform the qualification test at ambient conditions where the actual applied load shall be adjusted by the appropriate environmental and statistical knockdown factors derived from the design allowable test results for the same failure mode.

For all pressure vessels, pressurized structures, and pressure components, all qualification test requirements shall be demonstrated in accordance with the appropriate AIAA standards listed in Section 7.1, Table 4.

7 Special Structural Items

This section presents additional requirements for special structural items, including pressure vessels, pressurized structures, special pressurized equipment, heat pipes, flywheel rotors, beryllium structural items, cryo structures, hot structures, and sandwich structures. For items that already have published standards, the standard is identified. For items without published standards, specific requirements are defined in Section 7.2.

7.1 Special Structural Items with Published Standards

Table 4 provides a list of special structural items that shall be designed, fabricated, verified, qualified, and accepted based on a set of requirements specified in the corresponding published standards. Table 4 also summarizes important requirements contained in these standards.

Table 4 — Published Specific Requirements for Special Structural Items

Hardware Type	Design Ultimate Load/ Pressure	Acceptance Proof Load/ Pressure	Fatigue Life/Failure Mode	Damage Tolerance (Safe Life)	Post-Proof NDE	Corresponding Published Standard
Metallic Pressure Vessel	1.25x Limit Load , 1.5x MEOP	1.25x MEOP	Required for LBB Failure Mode, 4x Service Life	Required for Non-LBB Failure Mode, 4 Service Life	Required on welds	ANSI/AIAA S-080
Metallic Pressurized Structure	1.25x Limit Load, 1.25x MEOP	1.1x MEOP	Required for LBB Failure Mode 4 Service Life	Required for Non-LBB Failure Mode, 4 Service Life	Required on welds	ANSI/AIAA S-080
Composite Overwrapped Pressure Vessel	1.5x MEOP	1.25 x MEOP	Required for Non-hazardous LBB Liner, 4x Service Life	Required for Hazardous LBB Liner, 4 Service Life	Required visual inspection	ANSI/AIAA S-081
Battery Case	1.5x MEOP	1.25x MEOP	Required for LBB Failure Mode, 4 Service Life	Required for Hazardous LBB Case, 4 Service Life	Not Required	ANSI/AIAA S-080
Sealed Container	1.5 x MEOP	1.1x MEOP	Required for LBB Failure Mode, 4 Service Life	Required for Hazardous LBB, 4 Service Life	Not Required	ANSI/AIAA S-080
Cryostat Shell	1.5x MEOP	1.25 x MEOP	Required for LBB Failure Mode, 4 Service Life	Required for Non-LBB Failure Mode, 4 Service Life	Not Required	ANSI/AIAA S-080
Heat Pipe	2.5 x MEOP	1.5 x MEOP	Not Required	Not Required	Not Required	ANSI/AIAA S-080
Flywheel Rotor	1.225x MEOS	1.1x MEOS	Required for Unmanned System, 4 Service Life	Required for Manned System, 4 Service Life	Not Required	ANSI/AIAA S-096

7.2 Special Structural Items without Published Standards

This section addresses special structural items that shall be designed, fabricated, and tested in accordance with a specific set of requirements in addition to the general requirements specified in Sections 5.0 and 6.0.

7.2.1 Beryllium Structural Items

All beryllium primary and secondary structural items shall undergo a proof load test to 1.4 times limit load. No detrimental permanent deformation shall be allowed to occur as a result of applying the loads, and applicable alignment requirements must be met following the test. In addition, the following requirements shall apply.

a) When using cross-rolled sheet, the design shall preclude out-of-plane loads and displacements during assembly, testing, or service life.

b) In order to account for uncertainties in material properties and local stress levels, an ultimate design safety factor of 1.6 shall be used in margin of safety analysis.

c) Stress analysis shall properly account for the lack of ductility of the material by rigorous treatment of applied loads, boundary conditions, assembly stresses, stress concentrations, thermal cycling, and possible material anisotropy. The stress analysis shall take into account worst-case tolerance conditions.

d) All machined and/or mechanically disturbed surfaces shall be chemically milled to ensure removal of surface damage and residual stresses.

e) All parts shall undergo inspection for surface flaws per Section 5.5.1.2.

7.2.2 Cryo Structures and Hot Structures

In cases where a primary load condition on the structure is due to large thermal gradients or extreme temperature ranges, testing shall be performed in accordance with requirements specified by the procuring authority. As appropriate, testing shall include simulation of the temperatures and gradients on the structure, validation of analytical models at the component or subassembly level, and qualification of flight-quality hardware at higher levels of assembly.

A comprehensive test plan shall be developed and approved by the procuring authority. The test plan shall define what tests are required, the fidelity of the simulations, and the stages of development at which the tests are performed.

7.2.3 Sandwich Structures

Sandwich structures shall normally use vented core. The design shall utilize perforated core fitted with either perforated facesheets and/or panel edge members that allow gases present within the sandwich structures to vent safely during ascent into orbit.

In exceptional cases where venting is not acceptable, use of a non-vented design shall be approved by the procuring authority. The structure shall withstand pressure buildup without violating strength and stability requirements. For these cases, the integrity of each flight article shall be demonstrated by specially tailored proof tests, including high rate depressurization, to simulate the critical ascent environment. In addition, the facesheet-to-core bondlines shall be examined for debonds per the requirements of Section 5.5.1.2.

8 Documentation Requirements

8.1 Interface Control Documents

All interface control documents (ICD) related to structural items shall be recorded and subjected to review by the procuring authority.

8.2 Applicable (Contractual) Documents

All applicable documents shall be listed and a summary shall be prepared to show compliance with requirements. Deviations from the applicable documents shall be identified. Justifications for deviations shall be submitted to the procuring authority for review and approval. Approvals and denials of requested deviations shall be provided in written format as part of the documentation package.

8.3 Analysis Reports

When analysis is part of the verification of compliance with the requirements specified in Section 5.0, a corresponding report shall be prepared and submitted to the procuring authority for review and approval. The following sections specify the specific requirements for the analysis reports.

Reports shall include sufficient information describing the structural mathematical models and analyses performed to demonstrate the verification and validation of the results generated. Supporting analyses shall be documented and shall be traceable to engineering drawings, material data, and loading.

8.3.1 Stress Analysis Report

A stress analysis report documenting the analysis results shall be prepared. As a minimum, the report shall consist of

a) analysis inputs and assumptions, including:

  1) structure configuration and geometry;

  2) structure materials and their properties;

  3) limit loads, pressures, and temperatures for every loading case considered;

  4) safety factors for every loading case and structure element considered; and

  5) structural mathematical model description; including:

    i) assumptions and supporting justification; and

    ii) boundary conditions;

b) structural mathematical model checks and results;

c) failure modes considered;

d) failure criteria applied;

e) description or references for methods and software applied;

f) summary of significant analysis results; and

g) references.

The analysis shall be revised whenever changes of basic data occur and the revised results shall be documented.

8.3.2 Fatigue or Damage Tolerance (Safe Life) Analysis Reports

A fatigue or damage tolerance analysis report shall include the following as a minimum:

a) fatigue stress-life (S-N) data or fracture mechanics data, including fracture toughness (Kc) and fatigue crack growth rates (da/dN);

b) loading spectrum and environments;

c) NDE methods and corresponding initial flaw sizes for damage tolerance analysis;

d) analysis assumptions and rationale;

e) calculation methodology, including software description;

f) summary of significant results;

g) references.

8.3.3 Fracture/Impact Damage Control Plan/Report

As a minimum, the organization with primary responsibility for hardware development shall provide a Fracture Control Plan and/or Impact Damage Control Plan. The plan shall provide detailed hardware-specific fracture and/or impact damage control methodologies and procedures for testing, inspecting, handling, transportation, and operational life. The plan shall identify organizational elements and their responsibilities for activities required to implement the plan, including review of design and structural analyses, configuration control, and generation of required documentation such as a Fracture/Impact Damage Control Summary Report, etc.

The Fracture/Impact Damage Control Summary Report shall certify fracture control compliance, and the report shall be submitted to the procuring authority.

8.3.4 Inspection Reports

The inspection report is a compilation of inspection sheets used by the inspector to record results. As a minimum, the inspection sheet shall identify the following:

a) structural item by name and part number;

b) the material and condition;

c) type of NDE and sensitivity level;

d) a sketch of the item showing the area inspected and type of defects for which inspection was performed;

e) results of the inspection and the inspector's signature, date, and stamp.

8.3.5 Dynamic Analysis

The report shall include loads analysis methodologies, analysis model, forcing functions, modal frequencies, and results of analysis/test correlations.

9 Bibliography

CINDAS *Aerospace Structural Metals Handbook*
< http://www.lib.purdue.edu/eresources/wts/asmh.html>

CINDAS *Damage Tolerance Design Handbook*

ISO 14654 *Space Systems-Structural Design and Stress Analysis Requirements*

NASA CR 4708, Parts 1 and 2	*Composite Spacecraft Structures Design Guide*
NASA-STD-5001	*Structural Design and Test Factors of Safety for Spaceflight Hardware*
NASA-STD-5003	*Fracture Control Requirements for Payloads Using the Space Shuttle*
NASA-STD-7001	*Payload Vibroacoustic Test Criteria*
NASA-STD-7002	*Payload Test Requirements*
NASA-TP-2002-210780	*The New NASA Orbital Debris Engineering Model ORDEM2000*
ISO 14623	*Space Systems-Pressure Vessels and Pressurized Structures*
MIL-HDBK-340	*Military Handbook, Test Requirements for Launch, Upper Stage and Space Vehicles*
MIL-STD-401	*General Test Methods, Sandwich Constructions and Core Materials*
MIL-STD-810	*Environmental Test Methods and Engineering Guidelines*

American Institute of
Aeronautics and Astronautics

1801 Alexander Bell Drive, Suite 500
Reston, VA 20191-4344

www.aiaa.org

ISBN 1-56347-771-8