FAA
Commercial Space
Transportation

Guide to Verifying Safety-Critical Structures for Reusable Launch and Reentry Vehicles

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Commercial Space Transportation
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1.0 INTRODUCTION

1.1 Purpose

This guide provides acceptable methods of verifying safety-critical structures for reusable launch vehicles (RLV's). It defines structural safety factors and methodologies for demonstrating compliance with the Federal Aviation Administration (FAA), Office of Commercial Space Transportation (AST), regulations and for the safe operation of the applicant's proposed vehicle.

This guide serves as a companion document to the three FAA/AST publications listed below. It provides very specific guidance on verifying safety-critical structures per the guidelines referenced in the following documents.

- Guide to Reusable Launch Vehicle Safety Validation and Verification Planning, Version 1.0, September 2003 (see http://ast.faa.gov).
- Advisory Circular 431.35-2A – Reusable Launch and Reentry Vehicle System Safety Process, July 2005 (see http://ast.faa.gov).
- Guide to the Identification of Safety-critical Hardware Items for Reusable Launch Vehicle (RLV) Developers (see http://ast.faa.gov).

An applicant may use this document or an acceptable equivalent process to demonstrate compliance with 14 CFR 431 – Launch and Reentry of a Reusable Launch Vehicle and 14 CFR 437 – Experimental Permits. This guide makes no distinction between inhabited or uninhabited vehicles; however, structures of inhabited vehicles may be subjected to additional verification and safety requirements that are consistent with 14 CFR 460 – Suborbital Reusable Launch Vehicle Operations with Space Flight Participants and Crew. Potential RLV operators are strongly encouraged to start a pre-application dialogue with FAA/AST in the development phase of a proposed RLV program, so that any potential public safety concerns can be addressed as early as possible.

1.2 Scope

This guide provides a compilation of recommended structural design and acceptable methods of verification for RLV developers to use in demonstrating that their proposed vehicle's design and operations satisfy regulatory licensing requirements. This list of vehicle structural analysis and design criteria provides an acceptable basis for demonstrating that the structural systems can survive and perform to an adequate level of safety in all operating environments, including launch, flight, on-orbit, reentry, and recovery.

1.3 Acronyms

AIAA – American Institute of Aeronautics and Astronautics

AST – Office of Commercial Space Transportation

COPV – Composite Overwrapped Pressure Vessels

FAA – Federal Aviation Administration

MEOP – Maximum Expected Operating Pressure

MS – Margin of Safety

NDE – Nondestructive Evaluation

NASA – National Aeronautics and Space Administration

RLV – Reusable Launch Vehicle

1.4 Definitions

Acceptance test – A test performed on each article of the flight hardware to verify workmanship, material quality, and structural integrity of the design. In the protoflight structural verification approach, acceptance, proof, and protoflight tests are synonymous.

Acceptance test factor – A multiplying factor applied to the limit load or maximum expected operating pressure (MEOP) to define the acceptance test load or pressure (i.e. Acceptance test load = Acceptance test factor × Limit load or MEOP).

Allowable load – The maximum load or combination of loads which a structure or a component of a structural assembly can sustain during its service life under all expected conditions of operation or use without potential rupture, collapse, or detrimental deformation.

Creep – Time-dependent permanent deformation under sustained load and environmental conditions.

Detrimental yielding – Yielding that adversely affects the fit, form, function, or integrity of the structure.

Factors of safety (safety factors) – Multiplying factors to be applied to limit loads or stresses for purposes of analytical assessment (design factors) or test verification (test factors) of design adequacy in strength or stability.

Fatigue – Cumulative irreversible damage incurred in materials caused by cyclic application of stresses and environments resulting in degradation of load-carrying capability.

Fracture (safe-life) control – Rigorous application of engineering processes and methodologies, such as assurance management, manufacturing, and operations technology, dealing with the analysis and prevention of crack propagation.

Limit load – The highest anticipated load or combination of loads which a structure may experience during its service life under all expected conditions of operation or use.

Margin of safety[1] – The parameter used by the structural discipline to express structural capability in terms of structural requirements which include factors of safety. Margins of safety are

[1] Note – Load may mean stress or strain. Mathematical formulation applies to a single loading condition (mechanical, thermal, or pressure).

expressed for both yield and ultimate criteria. Margin of safety is mathematically expressed as the $\frac{\text{Allowable load}}{\text{Limit load} \times \text{Factor of safety}} - 1$

Maximum expected operating pressure – The maximum pressure that a pressure vessel may experience during its service life under all expected conditions of operation or use. It is the highest possible operating pressure taking into consideration maximum temperature, relief pressure, regulator pressure, and, where applicable, transient pressure excursions.

Pressure vessel – A container designed primarily for storing pressurized gases or liquids. Also defined as a container storing a pressurized gas or liquid which contains stored energy of 14,240 ft-lb [0.01 lb of trinitrotoluene (TNT) equivalent] or greater, based on adiabatic expansion of a perfect gas.

Pressurized component – A line, fitting, valve, or other part designed to contain pressure that is not (1) made of glass, (2) a pressure vessel, (3) a propellant tank, or (4) a solid rocket motor case.

Primary structures – The structural elements that transfer load along adjacent interfaces in the primary load path.

Proof test – A test performed on hardware to verify workmanship, material quality, and structural integrity of the design. In the protoflight structural verification approach, proof, acceptance, and protoflight tests are synonymous.

Proof test factor – A multiplying factor applied to the limit load or MEOP to define the proof test load or pressure (i.e. Proof test load = Proof test factor × Limit load or MEOP).

Protoflight test – A test performed on the flight hardware to verify workmanship, material quality, and structural integrity of the design. In the protoflight structural verification approach, protoflight, acceptance, and proof tests are synonymous.

Prototype test – An assessment of a scaled model or other test article to verify the structural integrity of the design. Prototype tests and qualification tests are synonymous.

Qualification test – An assessment of a scaled model or other structural article to verify the structural integrity of the design. Qualification and prototype tests are synonymous.

Qualification test factor – A multiplying factor to be applied to the limit load or MEOP to define the qualification test load or pressure (i.e. Qualification test load = Qualification test factor × Limit load or MEOP).

Safety-critical structure – A component whose performance or tolerance is essential for a system to operate in a manner that does not jeopardize public safety.

Secondary structures – Ancillary or auxiliary parts, including brackets to support individual components and attachments between primary structural elements, typically used to increase system robustness, provide redundancy, or both.

Service life – All significant loading cycles or events during the period beginning with manufacture of a component and ending with completion of its specified use. Testing, transportation, liftoff, ascent, on-orbit operations, descent, landing, and post-landing events should be considered.

Service life factor (life factor) – A multiplying factor to be applied to the maximum expected number of load cycles in the service life to determine the design adequacy in fatigue or fracture.

Structural failure – Rupture, collapse, excessive deformation, or any other phenomenon resulting in the inability of a structure to sustain specified loads, pressures, and environments or to function as designed.

Ultimate design load – Product of the ultimate factor of safety multiplied by the limit load (i.e. Ultimate design load = Ultimate factor of safety × Limit load).

Ultimate strength – Maximum load or stress that a structure or material can withstand without incurring a structural failure.

Verification – For the purpose of this guide, verification is the evaluation by test, demonstration, analysis, or inspection to determine that applicable safety-critical requirements for an RLV and its operations have been properly implemented.

Yield design load – Product of the yield factor of safety multiplied by the limit load (i.e. Yield design load = Yield factor of safety × Limit load).

Yield strength – Maximum load or stress that a structure or material is designed to withstand without incurring detrimental deformation.

2.0 GENERAL RECOMMENDATIONS: STRUCTURAL AND MECHANICAL VERIFICATION

2.1 General Structural Systems Recommendations

The structural system provides a basic framework for distributing external and internal loads resulting from all design flight and ground loads as well as from associated operational environments. These systems exist primarily to provide adequate strength and stiffness, such that the vehicle remains intact when exposed to all operating environments, including launch, flight, on-orbit, reentry, and recovery.

Structural verification of an RLV requires methodologies that accurately predict structural responses to applied loads and temperatures. Primary and secondary structures, including pressure vessels and mechanical systems, must be designed with adequate factors of safety and margins. Acceptable methods of determining whether a structure has met FAA safety requirements include verification by test, analysis, similarity, demonstration, and inspection. Acceptability of one method over another is predicated on the design, maturity, and proposed operations of the RLV system under consideration.

Applicants should conduct tests and analyses to demonstrate that the proposed vehicle structure qualifies for the expected mission environments. These tests and analyses must also demonstrate that the design of the hardware complies with the specified verification requirements, such as factors of safety, interface compatibility, structural integrity, workmanship, and associated elements of system safety. In addition, the appropriate mass properties and mechanical functionality must also be verified.

FAA/AST will evaluate the acceptability of a proposed set of verification methods during the pre-application consultation process and during the evaluation of the license or permit application. Components of the FAA/AST licensing or permit process include a pre-application consultation period and an application evaluation period made up of policy review, payload review, safety evaluation, financial responsibility determination, and environmental review. A detailed description of this process is available on-line at *http://ast.faa.gov/lrra/*.

2.2 Structural Verification Approaches for Design and Test Factors of Safety

The appropriate design and test factors for a given mechanical or structural flight hardware element depend on such parameters as the materials used, attachment methods (e.g., bonding), and verification approach. In applying the recommended minimum factors of safety specified in this guide, applicants must recognize that some safety-critical systems for inhabited vehicles may need to meet more stringent structural verification requirements that are consistent with 14 CFR 460 – Suborbital Reusable Launch Vehicle Operations with Space Flight Participants and Crew.

2.2.1 Prototype Testing: Design and Test Factors of Safety

The prototype approach is the standard accepted practice for verification of launch vehicles. A separate, dedicated test structure (a scaled model or test article), identical to the flight structure, is tested to demonstrate that the design meets the factor of safety requirements.

When using the prototype structural verification approach, the minimum ultimate design factors can be the same as the required qualification test factors for metallic structures as well as composite and bonded structures. Metallic structures should be verified to have no detrimental yielding at yield design load before testing to full qualification load levels.

2.2.2 Protoflight Testing: Design and Test Factors of Safety

The protoflight approach is a widely used acceptable alternative to prototype testing. Here the flight structure is tested to levels somewhat above limit stress (or load) but below yield strength. To preclude detrimental yielding during protoflight strength verification testing, the yield factor of safety for protoflight structural design must be greater than the test factor. Inspections and functionality assessments follow protoflight testing. When using the protoflight structural verification approach, applicants should use design factors that exceed the required acceptance or proof test factors to prevent detrimental yielding of the metallic structure or damage to the composite and bonded flight structure during testing.

2.2.3 Verification by Analysis

Verification by analysis involves mathematical modeling, computer simulation, or both, of the structural element. In the majority of cases, standard criteria cannot be specified for general use in designing structures for which no verification tests are planned. Structural designs generally should be verified by analysis and by either prototype or protoflight strength testing. Projects which propose to use the "no-test" (i.e. analysis only) approach are acceptable when verification by similarity of the structural element is possible, large factors of safety are used, or other methods prove infeasible, inadequate, or both. Wherever possible, this analysis only approach should be replaced with test or demonstration as the program evolves.

Examples of criteria on which to base "a verification by analysis only" approach are listed below.

- The structural design is simple (e.g., statically determinate) with easily determined load paths. It has been thoroughly analyzed for all critical load conditions. A high degree of confidence in the magnitude of all significant loading events exists.

- The structure is similar in overall configuration, design detail, and critical load conditions to a previous structure that was successfully test verified. Good correlation of test results to analytical predictions has been demonstrated.

- Critical, difficult to analyze structural elements have successfully completed development testing. Good analytical model correlation to test results has been demonstrated.

2.2.4 Probabilistic Methods

Design factors of safety and test factors are intended to conservatively compensate for uncertainties in the strength analysis. Current standard structural verification criteria are deterministic, and experience has shown these deterministic criteria to be adequate. The probabilistic method uses knowledge (or assumptions) of the statistical variability of the design variables to select design criteria for achieving an overall success confidence level. Any proposed use of probabilistic criteria to supplement deterministic factors of safety, within the context of an application for an RLV license or permit, must be approved by the FAA. The FAA approves such uses on a case-by-case basis.

2.3 Reliability and System Safety

The structural system must possess adequate strength and stiffness to withstand the maximum expected loads and pressures throughout its service life. It is expected that RLV developers will incorporate advanced technologies in designing and constructing future launch vehicles. The significance of the structural systems of these vehicles will always warrant a comprehensive analysis and test program in verifying that these new technologies are qualified for safe operation of the vehicle. Results of the structural verification effort provide input to the applicant's subsystems and system reliability efforts as part of the system safety process. For a detailed description, refer to Advisory Circular 431.35-2A – Reusable Launch and Reentry Vehicle System Safety Process. See *http://ast.faa.gov/rep_study/license_safe_report.htm*.

3.0 DETAILED RECOMMENDATIONS: STRUCTURAL AND MECHANICAL VERIFICATION

3.1 Applicability

The following criteria apply to RLV's, including their propellant tanks and solid rocket motor cases. These requirements present acceptable minimum factors of safety for use in analytical assessment and test verification of structural adequacy of safety-critical hardware. Designs must generally be verified by both structural strength analyses and tests. The factors are to be multiplied by the limit stresses, including additive thermal stresses. In addition, the structure must be verified not to exceed material allowable stresses (yield and ultimate) under the expected temperatures and other operating conditions. A complete verification approach includes frequent post-flight inspections to ensure structural integrity and durability.

3.2 Design and Test Factors of Safety

The test and design factors of safety stated in this guide are the recommended minimum required values for RLV safety-critical structures and apply to both mechanical and additive thermal stresses. Higher factors than those listed here may be required for proof testing if the proof test is to be used for fracture control flaw screening. If pressure or temperature has a relieving or stabilizing affect on the mode of failure, then for analysis or test of that failure mode, the unfactored stresses induced by temperature or the minimum expected pressure must be used in conjunction with the ultimate (factored) stresses from all other loads.

Tables 1 - 7 specify the recommended minimum test and design factors of safety for metallic structures; fasteners and preloaded joints; composite and bonded structures; glass; bonds for structural glass; pressurized vessels; and pressurized lines, fittings, and components. The design for these hardware items must preclude any detrimental permanent deformation or functional degradation of the system under the limit loads and acceptance or proof test loads for programs employing the protoflight verification approach.

3.2.1 Metallic Structures

Metallic structures may be assessed using either the prototype or the protoflight approach. Table 1 lists minimum design and test factors of safety for metallic structures, excluding fasteners.

Table 1. Recommended Minimum Design and Test Factors for Metallic Structures

Verification Approach	Design Factors		Test Factors	
	Ultimate Strength	Yield	Qualification	Acceptance or Proof
Prototype	1.5	1.0*	1.5	N/A or 1.05**
Protoflight	1.5	1.25	N/A	1.2

* Structure must be assessed to prevent detrimental yielding during flight, acceptance, or proof testing.
** Propellant tanks and solid rocket motor cases only.

3.2.2 Fasteners and Preloaded Joints

Table 2 lists minimum design and test factors for fasteners. The strength of fasteners used in preloaded joints must be assessed at zero and maximum preloads. For the zero preload case, the factor of safety must be applied to the induced fastener load. For the maximum preload case, the factor of safety need only be applied to the additional fastener load induced beyond the preload. In both cases, the preload plus induced fastener loads times the factor of safety must be less than the fastener ultimate strength (i.e., Ultimate strength > Preload + Induced loads × Factor of safety). Unless specifically designed to separate, all joints must maintain a factor of safety against separation. Minimum preload must be used in the separation assessment.

Table 2. Recommended Minimum Design and Test Factors for Fasteners and Preloaded Joints

Verification Approach	Design Factors		Test Factors	
	Ultimate Strength	Joint Separation	Qualification	Acceptance or Proof
Prototype	1.5	1.5	1.5	N/A
Protoflight	1.5	1.5	N/A	1.2

3.2.3 Composite and Bonded Structures

At a minimum, composite and bonded structures, excluding glass, should adhere to the design and test factors specified in table 3.

Table 3. Recommended Minimum Design and Test Factors for Composite and Bonded Structures

Verification Approach	Geometry of Structure	Design Factors	Test Factors	
		Ultimate Strength	Qualification	Acceptance or Proof
Prototype	Discontinuities	2.0*	1.4	1.05
	Uniform Material	1.4	1.4	1.05
Protoflight	Discontinuities	2.0*	N/A	1.2
	Uniform Material	1.5	N/A	1.2

* Factor applies to concentrated stresses.

3.2.4 Structural Glass

Table 4 lists recommended minimum design and test factors for pressurized and unpressurized glass. Structural integrity of all pressurized glass should be verified by both analysis and testing. Unpressurized glass may be verified by analysis only with an ultimate minimum design safety factor of 5.0. The prototype verification option is not available for glass. Protoflight tests of glass should be configured to simulate flight boundary conditions and loading. For glass protoflight testing, the total time during load, dwell, and unload should be as short as possible.

This testing should occur in an inert environment to minimize flaw growth. Care should also be taken to configure protoflight hardware to prevent overloading any bonded joints during test.

Table 4. Recommended Minimum Design and Test Factors for Structural Glass

Verification Approach	Loading Condition	Design Factors	Test Factors	
		Ultimate Strength	Qualification	Acceptance or Proof
Protoflight	Unpressurized	3.0	N/A	1.2
	Pressurized	3.0	N/A	2.0
Analysis Only	Unpressurized	5.0	N/A	N/A

3.2.5 Bonds for Structural Glass

Bonds for structural glass should be qualification tested on a separate article. Each flight article should be proof tested. Table 5 specifies the design and test factors.

Table 5. Recommended Minimum Design and Test Factors for Structural Glass Bonds

Design Factors	Test Factors	
Ultimate Strength	Qualification	Acceptance or Proof
2.0	1.4	1.2

3.2.6 Pressure Vessels, Lines, Fittings, and Components

The maximum design pressure of a pressurized system is the highest pressure defined by maximum relief pressure, regulator pressure, or temperature—including transient pressures. The design and test factors should be applied to the maximum expected operating pressure or MEOP. Where any combination of pressure regulators, relief devices, or thermal control systems (e.g., heaters) is used to control pressure, they should be two-fault tolerant to avoid exceeding the maximum expected operating pressure of the system. Pressure integrity should be verified at the system level by performing a leak check. Acceptable pressure vessels should demonstrate leak-before-burst. At the component level, fracture-critical pressurized systems may require additional tests, inspections, or both. Tables 6 and 7 list recommended minimum design and test factors for pressurized vessels, lines, fittings, and components.

Table 6. Recommended Minimum Design and Test Factors for Pressurized Lines, Fittings, and Components

Component	Design Factors	Test Factors
	Ultimate Strength	Proof
Lines and fittings with outside diameter < 1.5 inches	4.0	1.5
Lines and fittings with outside diameter ≥ 1.5 inches	2.0	1.5
Flexible hard lines	4.0	1.5
Line-installed bellows and heat pipes	2.5	1.5
Other components (e.g., valves, filters, regulators, or sensors) and their internal parts (e.g., bellows and diaphragms)	2.5	1.5

Table 7. Recommended Minimum Design and Test Factors for Pressurized Vessels

Design Factors	Test Factors	
Burst	Proof	Leak
1.5	1.25	1.0

3.3 Fatigue and Creep Life Recommendations

All non-fracture structural items should have adequate fatigue and creep life to achieve mission success. The recommended minimum service-life factor for fatigue and creep life assessments is 4.0. This recommendation applies in the following situations:

- Structures are made of well-characterized materials.
- Sufficient load-cycle data exists to account for all in-service environments.

3.4 Facture Control

For a reusable launch vehicle, all fracture-critical structural items should be damage tolerant or have adequate safe-life (fracture control). The minimum service-life factor for damage tolerant assessments should be 4.0. For metallic structural elements, the largest undetected crack that could exist in the fracture-critical element will not grow to failure when subjected to cyclic and sustained loads in the specified number of service lifetimes. In the case of composite structural elements, a broader range of flaw sizes should be considered. Metallic pressure vessels, as well as composite overwrapped pressure vessels, should demonstrate leak-before-burst during damage tolerant testing.

3.4.1 Damage Tolerance Analysis

For all metallic, glass, and ceramic fracture-critical parts, safe-life (damage tolerant) fracture mechanics analysis should be performed to verify that the parts meet the safe-life verification requirements. Undetected cracks should be assumed to be in critical locations and in the most unfavorable orientations with respect to the applied stress and material properties. Crack size should be based on crack-screening proof test limits or the detection capability of appropriate NDE technique used in the acceptance tests. Nominal values of facture toughness and fatigue crack growth rate data should be used in the analysis.

3.4.2 Damage Tolerance Testing

Damage tolerant (i.e. safe-life) testing for fracture-critical metallic, glass, and ceramic parts may be performed using the prototype, protoflight, or both approaches. For protoflight testing, a prefabricated crack of controlled size is induced in the flight-quality item and test in a representative environment. Prototype testing of the item is 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 the crack should correspond to the detection capability of the NDE to be imposed on the full-scale flight item.

Safe-life verification for fracture-critical composite structures should be performed by test only. The test for composite parts should be performed using full-scale, flight-quality (i.e. protoflight techniques), with prefabricated flaws. The size of the flaws should be based on the detection capability of the NDE to be imposed on the flight element. For components where neither safe-life analysis nor testing is appropriate, such as for some composite material failure modes, proof testing of each flight hardware item may be used to establish confidence in the damage tolerance or safe-life of a part.

4.0 ALTERNATE STRUCTURAL AND MECHANICAL VERIFICATION METHODOLOGIES

Situations may arise that are not covered in this guide or where an applicant either cannot or prefers not to meet a factor of safety requirement for a specific flight structure or hardware component. For example, future breakthroughs resulting from evolving technologies may eliminate the need for an applicant to meet a factor of safety requirement. In such cases, the applicant should propose an alternative or modified approach to verifying the strength adequacy of the proposed design. The organization with primary responsibility for the development of the structure or component should prepare a written risk assessment that justifies the use of the alternate approach.

5.0 SUMMARY

This guide contains a compilation of recommended structural verification methods for reentry and reusable launch vehicle (RLV) developers to use in demonstrating that the proposed design and operations of their vehicle satisfy Federal Aviation Administration, Office of Commercial Space Transportation, requirements. Applicants should use these methods or an acceptable equivalent process to demonstrate that the structural systems of an inhabited or uninhabited vehicle can survive and perform to an adequate level of safety in all operating environments. The FAA strongly encourages potential RLV and reentry vehicle operators to start a pre-application dialogue with the Office of Commercial Space Transportation, preferably in the development phase of a proposed RLV program, so that potential safety concerns can be addressed as early as possible.

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