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National Aeronautics and
Space Administration

# LOAD ANALYSES OF SPACECRAFT AND PAYLOADS

## NASA TECHNICAL STANDARD

# FOREWORD

This standard is approved for use by NASA Headquarters and all Field Centers and is intended to provide a common framework for consistent practices across NASA programs.

This standard was developed by the NASA Loads Standard Panel to minimize variations in methodologies, practices, and requirements for the conduct of load analyses among the NASA Centers. Such variations lead to misunderstandings and inefficiencies in the load analysis arena for large projects that generally involve more than one NASA Center.

This standard describes the accepted practices and requirements for the conduct of load analyses for payloads and spacecraft structures. Load regimes are identified. Requirements are set for establishing forcing functions and mathematical models and for performing analyses and verification of models by tests. Major methods of analyses, practices, and processes are identified.

Requests for information, corrections, or additions to this standard should be directed to the Structures and Dynamics Laboratory, Mail Code ED21, Marshall Space Flight Center, AL, 35812. Requests for additional copies of this standard should be sent to NASA Engineering Standards, EL02, MSFC, AL, 35812 (telephone 205-544-2448).

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FIGURES

# LOAD ANALYSES OF SPACECRAFT AND PAYLOADS

## 1. SCOPE

1.1 Scope. This standard defines the methodologies, practices, and requirements for the conduct of load analyses for payloads and spacecraft.

1.2 Purpose. This standard establishes general NASA policies for the definition of loads to be used in the design and development of payloads and spacecraft. Guidelines are prescribed to establish consistent practices and facilitate integration at the project and program levels.

Payloads and spacecraft shall be designed to maintain structural integrity and the required degree of functionality to ensure successful operation during all phases of the expected life cycle. Flight structures and systems shall consider static and dynamic load environments to be encountered during assembly, testing, transportation, launch, ascent, space operations, extraterrestrial operations, descent, and landing.

1.3 Applicability. This standard recommends engineering practices for NASA programs and projects. It may be cited in contracts and program documents as a technical requirement or as a reference for guidance. Determining the suitability of this standard and its provisions is the responsibility of program/project management and the performing organization. Individual provisions of this standard may be tailored (i.e., modified or deleted) by contract or program specifications to meet specific program/project needs and constraints.

## 2. APPLICABLE DOCUMENTS

2.1 General. The applicable documents cited in this standard are listed in this section only for reference. The specified technical requirements listed in the body of this document must be met whether or not the source document is listed in this section.

2.2 Government documents.

2.2.1 Standards. The following standards form a part of this document to the extent specified herein. Unless otherwise specified, the issuances in effect on date of invitation for bids or request for proposals shall apply.

NASA

| | | |
|---|---|---|
| NASA-STD-5001 | - | *Structural Design and Test Factors of Safety for Spaceflight Hardware* |
| NASA-STD-7001 | - | *Payload Vibroacoustic Test Criteria* |
| NASA-STD-7002 | - | *Payload Test Requirements* |

(Unless otherwise indicated, copies of the above standards are available from any NASA Installation library or documentation repository.)

2.2.2. Other Government documents. The following other Government documents form a part of this document to the extent specified herein. Unless otherwise specified, the issuances in effect on date of invitation for bids or request for proposals shall apply.

| | |
|---|---|
| NASA-SP-8077, September 1971 | *Transportation and Handling Loads* |

(Unless otherwise indicated, copies of the above document are available from any NASA Installation library or documentation repository.)

2.3 Order of precedence. Where this document is adopted or imposed by contract on a program or project, the technical guidelines of this document take precedence, in the case of conflict, over the technical guidelines cited in other referenced documents.

## 3. DEFINITIONS

For the purpose of this standard, the following definitions shall apply:

3.1 Component. An equipment item that is part of a payload or spacecraft and is treated as an entity for purposes of load analysis (examples are electronic boxes, batteries, electromechanical devices, and scientific instruments or experiments).

3.2 Limit load. The maximum anticipated load experienced by a structure during a loading event, load regime, or mission. Uncertainty factors associated with model uncertainty or forcing function uncertainty shall be incorporated into the limit load as reported. The factors of safety are not included in the limit load (refer to NASA-STD-5001, *Structural Design and Test Factors of Safety for Spaceflight Hardware*).

3.3 Payload. An integrated system that is carried into space on a launch vehicle for space operations. A spacecraft is considered a payload during the launch phase.

3.4 Primary structure. The structure that is the principal load path for all subsystems, components, and other structures.

3.5 Spacecraft. A self-contained vehicle or system that is developed to operate in space. A spacecraft consists of a support structure onto which are attached scientific instruments and related systems for communication, power, propulsion, and control.

## 4. REQUIREMENTS

4.1 Load regimes. A thorough understanding of the operation and performance requirements is necessary to ensure complete definition of load requirements for a spacecraft or payload.

a. During the design and verification of spacecraft and payloads, all load regimes to which the structure will be exposed shall be evaluated. Typical load regimes are described in 5.1.

b. If the structure will have multiple configurations during its mission, the load regimes each configuration will experience shall be identified.

c. Within each load regime, each source of loading shall be evaluated. Different load sources that can occur simultaneously shall be combined as specified in 4.2.5 and 4.3.5.

4.2 Requirements for payloads. The following requirements shall be applicable to payloads that experience the liftoff and ascent load regimes (5.1.1), as well as terrestrial landing (5.1.2.f) for Shuttle payloads.

Estimation of loads for the payload is an iterative process. Preliminary design loads are used for the initial sizing of the structure; then a mathematical model of the structure is developed and a preliminary load cycle is performed. Based on the resulting loads, structural sizing may need to be adjusted. The effect of design change due to loads or possibly to configuration changes can alter the static and dynamic properties of the structure, thereby changing the loads. Subsequent load cycles are needed to assess the changes in design, in launch vehicle and payload mathematical models, and in forcing functions.

4.2.1 Preliminary design loads. At the beginning of the design process, a set of preliminary loads shall be defined from previous programs or otherwise estimated. This preliminary design load data set shall be used for the initial sizing of structural elements to begin the load analysis process. Preliminary design loads should include conservatism to account for future models, forcing functions, and design changes.

4.2.1.1 Primary structure. Load factors for preliminary sizing of primary structure shall be provided by the launch vehicle organization based on the design load databases, existing load analysis results for similar payloads, and flight data. These load factors, usually prescribed in g's, are defined as the maximum total interface force in each axis divided by the payload weight. The resulting load factor is commonly described as the center of gravity (c.g.) load factor. Angular accelerations in radians per second squared (rad/sec$^2$) about the c.g. shall also be included when appropriate. In addition, frequency constraints on the payload design to avoid launch vehicle control system interaction or to avoid vehicle resonance shall be considered.

4.2.1.2 Components. Load factors for components are typically higher than payload load factors. Preliminary design load factors for components shall be obtained from a mass acceleration curve (5.4) or table that specifies load factors as a function of component weight, frequency range, structural support type, or other variables. They shall include effects of both transient and random loading and thus represent the total load environment for a flight event. The mass acceleration curve or table shall be based on available flight data, test data, analyses, and experience.

4.2.2 Development of a mathematical model for loads. Following the initial structural sizing, a mathematical model of the payload shall be developed using finite element methods. This model is then coupled with the launch vehicle (or upper stages) to perform one or more cycles of analyses in order to update and refine the loads in the payload. The model may also be used to evaluate loads due to the transportation environment.

4.2.2.1 Form of model. A payload dynamic mathematical model for coupled load analysis shall be generated using finite element methods. Finite element models are based on structural properties and geometry. The model may be a reduced version of a finite element model developed for stress analyses or may be a model developed specifically for load analysis. Regardless of the source, the modeling approach shall be aimed at producing accurate dynamic predictions (frequencies and mode shapes). The primary structure, including the launch vehicle/payload interface structures and their associated backup structures, shall be modeled in sufficient detail to provide accurate interface forces.

4.2.2.2 Resolution and fidelity. The frequency range for load analyses 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. Subsystem resonances and overall payload modes shall be modeled up to a model upper bound frequency, which shall be at least 1.4 times the cutoff frequency of the load analysis.

4.2.2.3 Model reduction. To obtain a loads model appropriate for coupling with the launch vehicle, the original finite element model may be reduced in size using static or dynamic reduction methods. If static reduction is used, the dynamic characteristics of the reduced model shall preserve the characteristics of the original model up to the model upper bound frequency.

4.2.3 Forcing functions. Forcing functions for events associated with the launch vehicle shall be developed by the launch vehicle organization. In general, launch vehicle organizations shall provide forcing functions that envelop flight experience and are intended to yield load responses which will not be exceeded with 99.87 percent probability.

4.2.4 Load cycles. A minimum of two load cycles shall be performed: a preliminary load cycle, which uses models based on initial sizing, and a verification load cycle which uses test-verified models.

4.2.4.1 Damping. Damping used for dynamic response analysis shall be based on test measurements of the actual structure, at amplitude levels that are representative of actual flight environments, or on experience with similar types of structures whenever possible. In the absence of measured damping data, low levels of damping shall be assumed. Damping of 1 percent is considered adequate for transient response analysis of typical structures.

4.2.4.2 Uncertainty factors in early load cycles. To reduce design impacts associated with load changes, uncertainty in the load definition shall be accounted for. This uncertainty may be accounted for by incorporating a factor in the results of early load cycles. This factor is used to account for immaturity in models and design, and for changes in launch vehicle models and forcing functions. General practice calls for a minimum factor of 1.5 for the preliminary load cycle. In subsequent load cycles, the factor shall be gradually reduced as the structural design and load analysis prediction mature. The uncertainty factor can be eliminated after the structure is built, the model is verified, and the forcing functions are finalized. However, if the model verification is inadequate for some reason, a factor shall be retained in the verification load cycle.

Use of an uncertainty factor to account for model variations may be avoided by using sensitivity analysis. Systematic changes are made to potentially uncertain payload properties, and the resulting loads are computed. The design load is taken from the worst case analyzed or from a statistical combination of all cases. Since payload loads are strongly dependent on the frequencies of the payload modes, frequency sensitivity (or “tuning”) analysis is a natural technique. By developing design loads that envelop a broad range of frequency shifts (for example, ±15 percent), the structural design is capable of handling the load increases that may occur as the design matures. This type of analysis has the advantage of increasing loads only for those items that are sensitive to frequency shifts.

4.2.5 Load combination. In cases where loads produced by different environments can occur simultaneously, these loads shall be combined in a rational manner to define the limit load for that flight event. Types of load combinations vary dependent upon the particular launch vehicle. For the Shuttle, common types of load combinations are transient loads with random vibration loads due to liftoff events and transient loads with thermally induced loads due to landing. For some expendable launch vehicles (ELV's), the transient loads and the random vibration loads due to liftoff do not occur simultaneously and are not combined. Loads due to pressurization of pressure vessels, venting, and installation misalignments should be included.

For liftoff, the simultaneously occurring environments are described in 5.1.1. The following specific requirements shall apply to design loads for components and their supporting interface structure:

a. The effects of low frequency transient loads and random vibration/acoustic loads shall be combined in a rational manner to determine the total load environment for liftoff.

b. For a component that weighs more than 500 kilograms (kg), the overall random vibration load may be assumed to be small relative to the low frequency transient load and therefore neglected.

c. For components weighing less than 500 kg, the appropriate method of load combination is dependent on how the low frequency and the random vibration/acoustic design environments of the event are specified. Typically, the maximum levels are defined as requirements for a flight event, such as liftoff, even if these maxima do not necessarily occur at the same time. The relative timing of the transient and random vibration environments is unique for each launch vehicle, but simultaneous occurrence of maximum low frequency transient and maximum random vibration load is improbable. Therefore, a root-sum-square (RSS) approach is acceptable for combining the maximum low frequency and maximum random vibration loads for the liftoff flight event. When the low frequency transient and random vibration environments are specified in a time correlated manner, a time consistent approach is also acceptable for combining the low frequency transient loads and the random vibration loads.

d. When an RSS approach to defining component loads is utilized, the maximum low-frequency and maximum random vibration load factor are RSS'd. The RSS'd values are then applied in all axes simultaneously. When the load combination is directly applied to member loads, the maximum random vibration and low frequency member forces are RSS'd.

e. When a time consistent approach to defining component loads is utilized, the low-frequency transient load factor and random vibration load factor are combined in a time consistent manner. When the load combination is directly applied to member loads, the member loads due to low frequency and random vibration are combined in a time consistent manner.

4.2.6 Verification of the payload mathematical model. Verification of the payload model by modal survey testing shall be performed to ensure the model is sufficiently accurate for load and deflection predictions (refer to NASA-STD-7002, *Payload Test Requirements*). Payload model verification may be accomplished by a combination of payload level and component level modal survey tests.

a. The goal of the modal survey test shall be to measure and correlate all significant modes below the model upper bound frequency, consistent with the model resolution requirement described in 4.2.2.2. Significant modes may be selected based on an effective mass calculation, but this set should be augmented by modes which are critical for specific load or deflection definition.

b. Boundary interface degrees of freedom that carry loads in the flight configuration shall be constrained in verification testing. If alternate boundary conditions are utilized, additional testing and analysis shall be required to verify effects of the alternate configuration.

c. The modal survey test shall include appropriate techniques to identify nonlinearities. Varying input excitation levels and reciprocity checks are commonly utilized for linearity assessment. Significant nonlinearities may require sinusoidal testing at multiple force levels. In the case of nonlinearities that affect load predictions, the frequencies and mode shapes should be obtained from the highest practical excitation levels. The load model must then be developed from the available data using best engineering judgment, and the effects of the resulting model uncertainty on the loads must be incorporated.

d. Agreement between test and analysis natural frequencies shall, as a goal, be within 5 percent for the significant modes.

e. Accurate mass representation of the test article shall be demonstrated with orthogonality checks using the analytical mass matrix $[M_A]$ and the test mode shapes $[Ø_T]$. The orthogonality matrix is computed as $[Ø_T]^T[M_A][Ø_T]$. As a goal, the off-diagonal terms of the orthogonality matrix should be less than 0.1 for significant modes based on the diagonal terms normalized to 1.0.

f. Mode shape comparisons shall be required via cross-orthogonality checks using the test modes $[Ø_T]$, the analytical modes $[Ø_A]$, and the analytical mass matrix $[M_A]$. The cross-orthogonality matrix is computed as $[Ø_T]^T[M_A][Ø_A]$. As a goal, the absolute value of the cross-orthogonality between corresponding test and analytical mode shapes should be greater than 0.9; and all other terms of the matrix should be less than 0.1 for all significant modes. Additionally, qualitative comparisons between test modes and analytical modes using mode shape animation and/or deflection plots shall be performed.

g. Modal damping may be measured for each significant mode as part of the modal testing.

h. Failure to satisfy the goals of items d through f shall be accompanied by an assessment of the effects of model uncertainty on critical loads.

i. Under certain conditions, simplified model verification by sinusoidal sweep test is allowed. The natural frequencies of the payload or component shall be calculated with the flight configuration boundary conditions fixed. A payload or component with a minimum frequency higher than the model upper bound frequency (4.2.2.2) can substitute sinusoidal sweep vibration testing to verify the frequency. In this case, mode shape correlation is not required.

4.3 Requirements for spacecraft. The following requirements shall be applicable to spacecraft that can experience a variety of load regimes during operational phases, depending on the specific mission (see 5.1.2). In many cases, these load regimes are more benign than the liftoff load regime and terrestrial landing. However, the spacecraft configuration may change as deployments and separations occur, and the susceptibility of the structure may be different.

4.3.1 Preliminary design loads. For use in preliminary design, the spacecraft developers shall develop envelopes that bound the accelerations for components. These component load factors may be defined as a function of component weight, frequency range, structural support type, or other variables. The load factors should be based on available flight data, test data, analyses, and experience.

4.3.2 Development of mathematical models. Mathematical models shall be developed as needed to support load predictions for spacecraft. Depending on the load regime, these models may take the form of rigid body models, kinematic models of mechanisms, or finite element models. Finite element models for dynamic response analysis shall be developed following the guidelines of 4.2.2. Verification of spacecraft dynamic models may require off-loading systems that simulate the free-free boundary conditions of the spacecraft. In cases where model verification cannot be performed satisfactorily, conservative uncertainty factors shall be applied to the predicted loads.

4.3.3 Forcing functions. Forcing functions for events associated with the spacecraft are developed by the spacecraft organization as needed. The following general requirements shall apply:

4.3.3.1 Basis for forcing functions. Analytical predictions, ground test data, and flight data shall be utilized to the maximum extent possible for the forcing function definition.

The effects of variations and tolerances of parameters that govern the forcing functions shall be considered.

The goal is to provide forcing functions that envelop any flight experience and are intended to yield load responses which will not be exceeded with 99.87 percent probability. Two acceptable approaches are worst-on-worst combinations of parameters and a Monte Carlo selection of parameters. In both approaches, accurate knowledge of statistical variation of parameters is desired. For the Monte Carlo approach, an appropriate distribution shall be defined for each parameter so a value can be randomly selected. In the worst-on-worst approach, maximum or minimum values of key parameters may be combined simultaneously to define forcing functions. In the worst-on-worst approach, a lower value of dispersion (e.g., 2 sigma rather than 3 sigma) may be used since extreme values of multiple parameters are combined directly in a single or limited number of cases.

4.3.4 Load cycles. Estimation of loads for spacecraft may involve an iterative process, as described in 4.2. for payloads. Often, the loads experienced by spacecraft structure are affected by the design and sizing of the structure itself. Therefore, preliminary loads shall be required, which must then be refined as the design matures.

4.3.5 Load combination. In cases where loads produced by different environments can occur simultaneously, these loads shall be combined in a rational manner to define the limit load for that flight event. Common types of load combinations include static pressure loading occurring at the same time as turbulent buffeting during atmospheric entry and thermal loads occurring at the same time as deployment release loads and/or end of travel loads.

## 5. NOTES

(This section contains information of a general or explanatory nature which may be helpful but is not mandatory.)

5.1 Typical load regimes for payloads and spacecraft. Payloads and spacecraft can experience a variety of load regimes during their service life, depending on the specific mission.

5.1.1 Liftoff and ascent load regime. The launch and ascent environments vary depending on the particular launch vehicle used. Load events may include engine ignition, launch pad release, liftoff, maximum dynamic pressure, transonic buffet, maximum acceleration, separations, engine shutdowns, thrust oscillations, and pogo.

The major induced environments during liftoff and ascent are typically produced by propulsion system operation. The launch vehicle thrust produces loads that are transmitted through the structure. The ignition transients of the propulsion system and launch pad release produce dynamic loading. The propulsion system also produces acoustic excitation that is amplified by reflections when still in proximity to the launch pad. Acoustic excitation is also produced by ascent aerodynamics. The magnitude of the transmitted energy at the launch vehicle/payload interface is dependent upon the particular launch vehicle.

Natural atmospheric winds and pressure as a function of altitude produces loads during the launch/ascent of all launch vehicles. The effect of venting on structural loading during ascent (and descent) may be significant. Winds can produce loading on the launch vehicle from prelaunch through atmospheric ascent. The loading is transmitted from the launch vehicle to the payload. Propulsion system thrust oscillations, as well as structural coupling with the control system, can also result in significant payload loading.

There are three basic types of flight environments that generate dynamic loads on payload components:

a. The low-frequency dynamic response, typically from 0 to 50 Hertz (Hz), of the launch vehicle/payload system to transient flight events.

b. The high-frequency random vibration environment, which typically has significant energy in the frequency range from 20 Hz to 2000 Hz, transmitted from the launch vehicle to the payload at the launch vehicle/payload interfaces.

c. The high frequency acoustic pressure environment, typically 31 Hz to 10,000 Hz, inside the payload compartment. The payload compartment acoustic pressure environment generates dynamic loads on components in two ways: (1) by direct impingement on the surfaces of exposed components, and (2) by the acoustic pressure impingement upon the component mounting structures, which induces random vibrations that are mechanically transmitted to the components.

Combinations of these loads occur at different times in flight and shall be examined for each flight event.

5.1.2 Other load regimes. Load regimes other than the liftoff and ascent regime are generally more benign but shall be considered. For some operational regimes, the configuration of the payload or spacecraft may change as deployments and separations occur, and the susceptibility of the structure may be different.

a. Assembly. Assembly of components or integration of payloads can sometimes produce structural forces, such as misalignment of parts and fasteners, shear pin connections, bolt torque, etc.

b. Ground handling and transportation. The ground handling and transportation environments can be characterized with static, vibration, and shock inputs (refer to NASA-SP-8077). These environments are generally limited, by design, to be less than launch and landing loads but should be assessed as part of the set of load requirements. Vibration loads for transport are classified by different modes of travel including aircraft, rail, ships, or trucks.

c. Ground testing. Testing of payloads and spacecraft involves a variety of excitation inputs that cover a range of amplitudes and frequencies. The loads experienced during testing may exceed flight loads and must be considered in the design. All planned tests should be considered, including static, vibration (random, sine, etc.), acoustic, shock, pressure, spin balance, impact, and deployment tests. The effects of test configurations and boundary conditions should be assessed. Testing may require exposing payloads to operational thermal environments associated with cryogenics, orbital day/night transitions, extraterrestrial operations, etc.

d. On-orbit deployment. Deployable spacecraft, or items such as solar arrays, antennas, booms, radiators, etc., that deploy from a spacecraft must be designed to account for loads induced due to their deployment action. Deployment may include initial release, extension, spinup, unfolding, and/or end of travel. Partially deployed Shuttle payloads experience transient loads due to firings of the attitude control system and orbital maneuvering system.

e. On-orbit assembly. Assembly loads resulting from crew or robotics operations required to configure a payload or spacecraft to an intermediate or operational state must be considered. Assembly loads also may occur due to docking of two spacecraft and from berthing of components with a robotics or otherwise automated device. Crew or robotics translation, manipulation, installation, and/or removal of equipment or components for maintenance or comparable activities require assessment. Loads from operations that may occur simultaneously or in close sequence must be combined in a rational manner.

f. Descent and landing. Terrestrial descent and landing are transient loading environments where payloads and spacecraft will be subjected to static and dynamic loading. The descent maneuvers will produce static load conditions from inertial accelerations and pressure changes with altitude. The landing gear impact (touchdown) conditions produce significant dynamic loading. For the Shuttle, the thermal environments resulting from orbit operations produce structural loads that are combined with other descent/landing loads. Loads induced by recovery operations after landing, including lifting and handling, shall be considered.

g. Space operations. Spacecraft will generate or incur mechanically and thermally induced loads while operating in space. These loads may result from spacecraft booster thrust, spin/despin, and attitude control; from mechanical sources like rotating machinery and deployment or retraction devices; and from crew and robotics activity. Thermally induced loads encountered during flight operations may result from external sources such as day/night transitions associated with planetary orbit or internal heat sources and sinks.

h. Extraterrestrial operations. Extraterrestrial operations are those that occur in the atmosphere or on the surface of a planetary satellite or planet other than Earth. These operations can induce loading from descent and landing, surface excursion, mechanical functions, pressurization, and launch. The loads induced by these events are dependent on the design concept utilized. Load attenuation mechanisms are generally utilized to limit landing impact loads. Other spacecraft-unique functions or operations that produce structural loading should be considered.

5.2 The load cycle process. In most cases, structural loads are dependent not only on the external environment but also on the structural properties of the spacecraft or payload. This means the sizing of structural members can influence the loads. At the same time, the sizing is often governed by the need to withstand the loads. As a result, structural design and load analysis are normally an iterative process.

The load cycle analysis process is iterative and the number of iterations is variable. As a minimum, the load cycle shall consist of a preliminary design cycle and a verification cycle. The verification load cycle is performed using test-verified models. For programs that require optimization to achieve minimum weight for the structure, additional load cycles are typical. The load cycle analysis process shall be carefully planned so as to provide maximum benefit to the overall program development plan and schedule.

Following the initial structural sizing using preliminary design loads, dynamic load analyses shall be used to refine payload loads. The primary steps in a typical launch vehicle load cycle analysis process are shown in Figure 1. A similar approach may be used for any dynamic loading event.

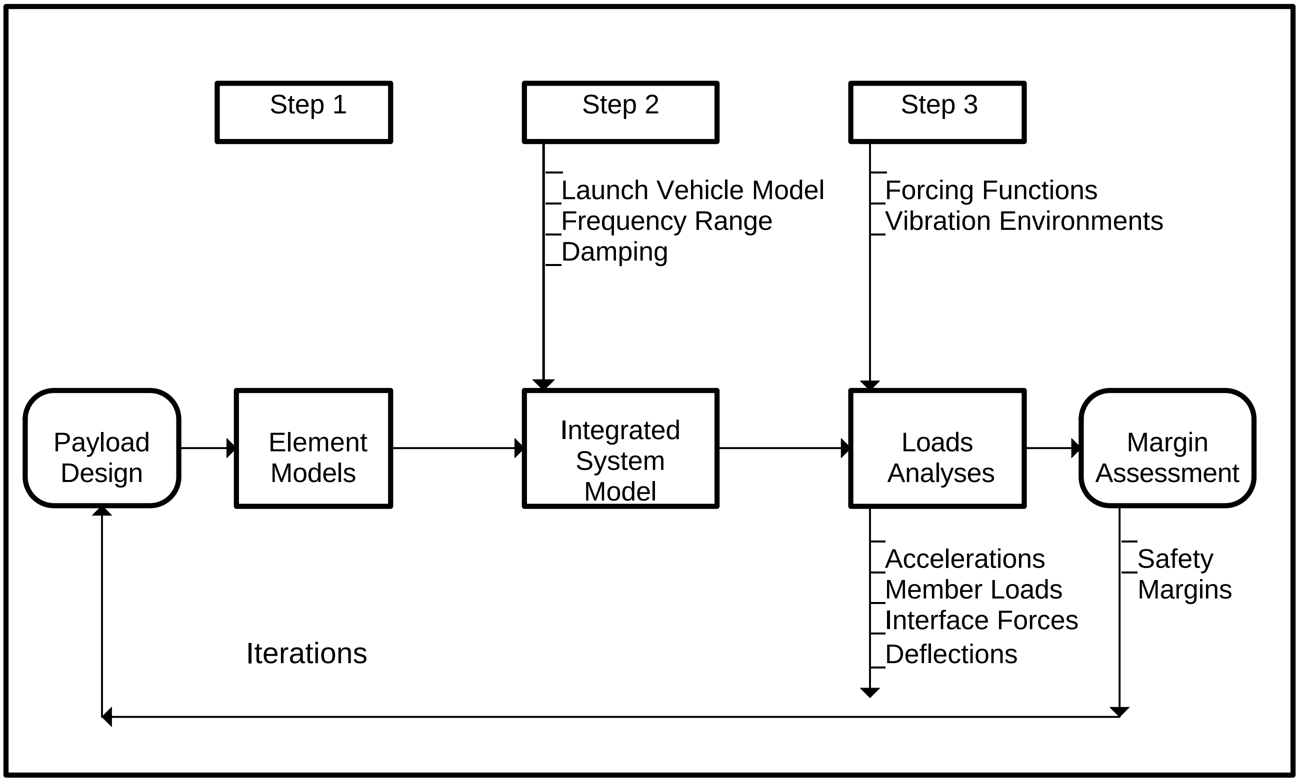


FIGURE 1. The Load Cycle Analysis Process

The steps in this process are described as follows:

a. Step 1 of the load cycle process. Finite element models of elements comprising the payload are developed from structural properties and geometry. For the first load cycle, the properties and geometry of the initial design shall be used. For subsequent load cycles, these models are updated.

b. Step 2 of the load cycle process. The payload element models are combined with models of launch vehicle elements to form an integrated system model.

c. Step 3 of the load cycle process. Forcing functions representing the specific flight environments are applied to the integrated system model to obtain payload structural response. Appropriate uncertainty factors are applied at this time. The results of these analyses shall be used to update/revise the design load data set as required and are subsequently used for structural margin assessment.

5.3 Analysis methods. Analysis methods fall into three general categories (static, transient, and random vibration analyses). Static analysis is used to predict distribution of loads and displacements in a structure due to slowly varying applied forces. This type of analysis is also used for thermal loads, which arise from temperature changes in the structure. Transient analysis is used to predict loads resulting from applied forces that are rapidly varying and deterministic functions of time. Random vibration analysis deals with applied forces that are not deterministic but are known only in terms of statistical average properties. This type of analysis predicts statistical averages of loads in the structure resulting from applied random forces.

5.3.1 Static load analysis. Static load analysis is suitable for load events in which the applied forces vary slowly with time. Such forces have frequency content much lower than the natural frequencies of the structure, so that dynamic response is not induced. These events are commonly called quasi-static. Examples of static environments include: maximum acceleration during ascent, descent maneuvers, steady spin, installation misalignment, and temperature variations.

The objective of static load analysis is to define the resulting load distribution throughout the structure. This load distribution may be defined using tools such as free body diagrams in simple cases. Finite element analysis is recommended for complicated or redundant load paths.

When performing static analysis with load factors, inertial (“g”) forces are applied to the structure along the various axes. Inertial forces in all three axes (including rotations, if appropriate) shall be applied simultaneously, including sign combinations. Interface boundary conditions shall be consistent with the coupled configuration.

Static analysis is also used to predict forces and displacements due to specified temperature variations. The thermal strain caused by the specified temperatures, along with the system constraints, results in the predicted forces and displacements.

5.3.2 Transient load analysis. Transient analysis is appropriate when the loading environment can be represented by deterministic rapidly varying forces. Examples of transient events are engine ignition and shutdown, launch pad release, staging, control system operation, and landing impact.

This type of analysis requires development of a dynamic model of the complete dynamic system. In the case of launch load analyses, the model normally consists of the payloads coupled to the full launch vehicle. The forcing functions are applied; the equations of motion are solved; and time histories of the resulting displacements, accelerations, interface forces, and member forces are recovered.

Statistical variation of parameters governing the forcing functions is accommodated by generating multiple cases of forcing functions for a single flight event. After all cases are analyzed, the maximum transient load is taken as the largest load from any of the cases.
The frequency range of transient load analysis is limited by the accuracy of both the model and the forcing functions. For Shuttle liftoff and landing, transient analysis generally accounts only for frequencies from 0 to 35 Hz. For some expendable launch vehicles, significant axial loads are generated at higher frequencies during engine cutoff events, and transient analyses must be run to 60 Hz or higher. For other events such as docking, robotics berthing, plume impingement, and spacecraft landing, the modal content must be selected to adequately capture the dynamic response.

Damping used for transient load analyses shall be based on test measurements of the actual structure at amplitude levels that are representative of the actual flight environment or experience with similar types of structures whenever possible. In the absence of measured damping data, low levels of damping shall be assumed. Damping may be incorporated into the transient analysis as modal damping on the coupled system modes or as modal damping on the modes of the components. In some cases, physical dampers may be included in the finite element models. When damping is applied to the component modes, the coupled system damping matrix is not diagonal. The equations of motion shall be solved with the off-diagonal terms of the damping matrix included.

The direct applicability of transient load analysis results to stress analysis is dependent on the fidelity of the dynamic model used in the analysis. Stress recovery directly from dynamic models for load analysis shall only be utilized for relatively simple load paths, where the models have the fidelity necessary to accurately calculate stress. Maximum and minimum component accelerations may be used as a basis for component stress analysis using static load factors.

5.3.3 Random vibration load analysis. Some load environments must be treated as random phenomena, when the forces involved are controlled by non-deterministic parameters. Examples include high frequency engine thrust oscillation, aerodynamic buffeting of fairing, and sound pressure on the surfaces of the payload.

Random vibration analysis describes the forcing functions and the corresponding structural response statistically. It is generally assumed the phasing of vibration at different frequencies is statistically uncorrelated. The amplitude of motion at each frequency is described by a power spectral density function. In contrast to transient analysis which predicts time histories of response quantities, random vibration analysis generates the power spectral densities of these response quantities. From the power spectral density, the root mean square (rms) amplitude of the response quantity is calculated. Random vibration limit loads are typically taken as the 3-sigma load (obtained by multiplying the rms load by 3). Damping used for random vibration analyses will be based on test measurements or experience with similar types of structures, materials, and analysis methods.

Random vibration analysis shall only be utilized for load predictions when the dynamic model has adequate fidelity in the frequency range of the analysis. The boundary conditions for the model shall correspond to the attachment to the supporting structure. The random vibration excitation may consist of accelerations at the interface degrees of freedom or sound pressure on the surfaces of the structure. Interface accelerations are represented by power spectral densities that envelop measured or predicted accelerations. Sound pressure levels are described in third-octave bands, representing average pressure amplitude over the band.

An important feature of random vibration analysis is the correlation between input accelerations and spatial correlation of pressure forces. A typical assumption for base drive analysis is that interface accelerations in different directions are uncorrelated.

In simple base drive cases, when the component can be represented as a single dynamic degree of freedom, the Miles equation gives a useful approximation to the rms response of the system. For more complicated structures, random vibration analysis can be performed when a finite element model with adequate fidelity exists.

A conservatism of performing random vibration base drive analysis is that dynamic coupling between the component and its supporting structure is not modeled. The impedance effect (vibration absorption) the component resonances have on the interface accelerations is not captured since there is no feedback between the response and the input. This is the same phenomenon that can cause component vibration tests to be overly conservative compared with the flight environment. The effect is most pronounced for primary modes of the payload or component (those with high effective mass), where the impedance can bring about a significant reduction in response in the true environment.

Most payloads are acoustic tested to measure vibration levels associated with the acoustic environment (refer to NASA-STD-7001, *Payload Vibroacoustic Test Criteria*, and NASA-STD-7002, *Payload Test Requirements*). Such tests are typically late in the payload development and thus serve as verification of design environments used for spacecraft components.

5.4 Mass acceleration curve. The concept of the mass acceleration curve has been successfully used for many years for the preliminary design of payloads. In essence, it has been observed that the acceleration of physical masses of a payload are bounded by a curve. The lighter the mass, the higher the corresponding acceleration. This observation is true for both transient and random vibration analyses.

The development of such a curve shall be based on previous experience with the launch vehicle and, if possible, shall incorporate results from previous transient and random vibration analyses, as well as any available flight data. In most cases, a single curve can be developed for a given launch vehicle configuration that applies to a broad class of payloads.

5.5 Key word listing

Forcing functions
Load analysis
Loads combination
Loads regimes
Mathematical models