ROLES OF TESTING IN DESIGN AND VERIFICATION OF THE FALCONSAT-2 STRUCTURE

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Abstract

FalconSat-2 (FS2) is a micro-sat being developed at the United States Air Force Academy (USAFA), to be launched as a Hitchhiker payload on the Space Shuttle. The program adopted the philosophy of testing early and often, recognizing budget constraints and limited analysis capabilities of the staff, which consists mostly of cadets. The objective of this program is mainly to teach, and testing, combined with theory, is a great way to learn. Early development testing on a shaker table of a crude but representative structure provided useful information for designing the flight structure and also for improving the accuracy of a simple finite-element model. Analysis is being used selectively to provide the most value. Low-cost testing will be the final verification of most structural requirements. The test program is not complete as of the date of this paper, but we hope to demonstrate structural integrity to the Space Shuttle Safety Panel without a single color stress plot!

Keywords: verification, testing, qualification, acceptance, development, structures, design

Overview of the FalconSat Program

FalconSat-2 is the third in a series of small spacecraft being developed at USAFA, following FalconGold (1996 – 1997) and FalconSat-1 (1998 – 1999). In the FalconSat program, undergraduate cadets design, build, test, and operate small satellites to support DOD scientific payloads. The main objective is to provide an opportunity for USAFA cadets to "learn space by doing space" in a safe, supervised environment.

The mission for FS2 is to investigate plasma depletions ("bubbles") in the ionosphere, using the Miniature Electrostatic Analyzer (MESA) payload, with the goal of understanding the effects of such bubbles on satellite transmissions. The spacecraft has its own systems for power, communications, command and data handling, and attitude determination. The structure is cubic, 12.5 inches (31.75 cm) per side, and the full spacecraft weighs about 40 lbs (18 kg mass). Figure 1 shows the configuration. Launch is planned for early 2003 as a Hitchhiker payload aboard the Space Shuttle.

The launch environments specified in the Customer Accommodations and Requirements Specification (CARS) [NASA, 1999] include

- quasi-static accelerations: 11 g at the c.g. in each of three orthogonal directions, along with 85 rad/s^2 rotational acceleration acting in each axis, all acting simultaneously
- base-driven random vibration, peaking at 0.075 g^2/Hz acceptance (0.15 g^2/Hz qualification).

The CARS also specifies that Hitchhiker payloads have a fundamental frequency above 50 Hz or be represented in the verification loads cycle (VLC) for the applicable mission with a test-correlated finite-element model. If the fundamental frequency is confirmed by test to be above 50 Hz, only the payload's mass properties must be represented in the VLC.

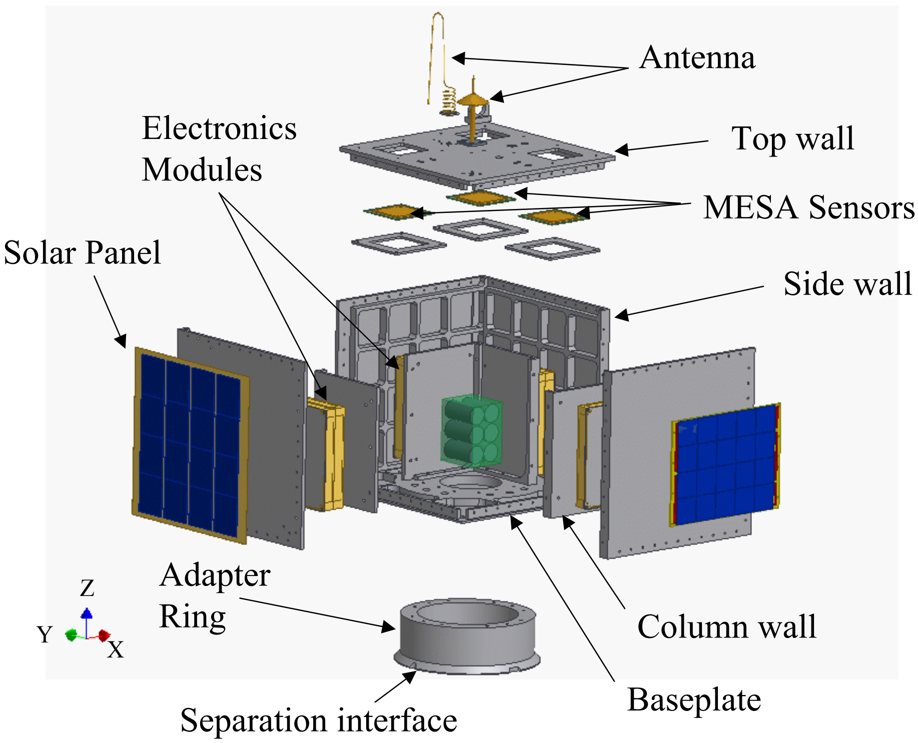

Fig. 1. **FalconSat-2 Configuration, Exploded View.** The spacecraft will fly inside a canister. The cubic structure will bolt to a cylindrical adapter ring, which will attach to the Shuttle's Pallet Ejection System with a band clamp. Once the Shuttle's primary mission is accomplished, the astronauts will open the lid of the canister, and FalconSat-2 will eject.

Program Philosophy

For structural design and verification, the FalconSat philosophy is to test early and often. Many space programs consider testing to be expensive, but we have found the opposite is true for small spacecraft. When manufacturing and test facilities are available, building and testing representative development hardware is less expensive—and usually more meaningful—than detailed analysis. This philosophy also provides an effective building-blocks approach to verification and risk reduction. Table 1 summarizes the structural test program.

TABLE 1. Structural Test Program for FalconSat-2. Thermal vacuum testing and separation/shock testing are also planned.

Test Phase	Test Article	Objectives	Planned Tests	Test Levels and Criteria
Development	Engineering model (representative structure, complete with operational equipment)	Obtain information to improve the final design and help plan the qualification and acceptance test phases	- Sine sweep -Random vibration - Sine burst	Low (used to determine natural frequencies) 3 dB above acceptance levels in each of 3 orthogonal axes 1.4 times limit acceleration in each of 3 orthogonal axes
Qualification	A test-dedicated unit built to the same design and with the same processes as the flight unit; full assembly, with all equipment	Demonstrate the FS-2 structural design is adequate for strength and fatigue life, with margin that should cover unavoidable variation in workmanship	- Sine sweep - Random vibration - Sine burst	Low (used to determine natural frequencies) 3 dB above acceptance levels in each of 3 orthogonal axes, 3 minutes per axis 1.4 times limit acceleration in each of 3 orthogonal axes
Acceptance	Flight unit; full assembly, with all equipment	Verify process control and workmanship	- Sine sweep - Random vibration - Sine burst	Low (used to determine natural frequencies) Acceptance levels in each of 3 orthogonal axes, 1 minute per axis Limit acceleration in each of 3 orthogonal axes

For FalconSat, frequent testing also better satisfies the objective of teaching cadets. A small group of cadets is learning and doing some structural analysis, but available time severely limits how much can be taught in this field. Most of the structural analysis is being done by the author, as a part-time consultant, to steer the design, simplify testing, interpret test data, and satisfy NASA's safety requirements.

Another philosophy has been to keep everything as simple as possible. Weight is not critical, so the structural design uses ductile metals and A-286 threaded fasteners, which are less sensitive to manufacturing processes than composite materials and bonded joints. Structural parts are machined from 6061-T6 aluminum alloy plate, which is inexpensive, ductile, easy to machine, and resistant to corrosion. The walls of the box structure have stiffening ribs machined in an orthogrid pattern.

Approach to Structural Design and Verification

The process used for developing the FS2 structure is as follows:

1. Develop a conceptual configuration for FS2.

   As shown in Fig. 1, the conceptual configuration establishes load paths and locations for the spacecraft's equipment.

2. Design a structure for an engineering model (EM) .

   The EM was a development unit. Its purpose was to pathfind manufacturing, integration, and test; identify design improvements; and acquire information that would help make the flight design more predictable. The EM structure was designed without the aid of analysis to be representative of the eventual final design but considerably stiffer and heavier. The machined baseplate (see Fig. 1) is the critical structural part, stressed by bending, mostly under lateral (X and Y) loading. It was designed as a nearly solid 0.75"-thick aluminum plate to make its failure unlikely during vibration testing.

3. Simplify the specified loads by reducing them to equivalent single-axis loads for test.

   Because each of the six axes of specified accelerations (three translations and three rotations) can act in any direction, together they present 64 (2^6) load cases. One of the elements of effective structural test planning is developing simplified test load cases that envelop the effects of the specified loads. It's best to do this early in the program so the structure can be designed to withstand the planned tests. Anytime a set of load cases is reduced to a fewer number of "equivalent" cases, some amount of excessive loading in some parts of the structure is unavoidable. Understanding weight criticality of the flight hardware is key to identifying the best extent of simplification.

   For FalconSat-2, reducing cost and time has been much more important than minimizing weight. We plan to do all structural testing on an electrodynamic shaker. To keep things simple, we decided to do the sine-burst tests in the same three axes (shown in Fig. 1) as the random-vibration tests. To ensure the sine-burst tests will adequately verify strength, we had to derive single-axis accelerations that would stress the structure at least as much as the 64 combinations of specified loads.

   As mentioned above (Step 2), the baseplate is the critical structural part. It attaches to the separation ring with a circle of bolts on a diameter of about eight inches. With rough analysis, based on the geometry and mass of the EM (along with assumptions needed to estimate center of gravity and mass moments of inertia), we calculated the peak bolt tension for the specified loads. Using the same assumptions, we then calculated the uniform lateral acceleration that would cause the same bolt tension.

   We followed a similar process for several other potentially critical locations in the structure. As a result, we concluded that ±22.5-g single-axis acceleration applied in X or Y would stress all the areas of concern at least as much as the specified limit loads. We rounded the acceleration up to 25 g to account for uncertainty, and we decided to perform the sine-burst tests to 25-g limit in each axis. For development and qualification testing, we increased the acceleration to 35 g in each axis, based on an ultimate factor of safety of 1.4. Finally, we replaced the specified load cases with the new simplified, single-axis cases for use in design. In other words, we planned from the start to design the flight structure to be able to withstand the test loads.

4. Test the EM for sine sweep, random vibe, and sine burst.

   The EM weighed about 47 lbs, counting the adapter ring. We instrumented the EM with tri-axial accelerometers at the center of the top (+Z) panel, one of the corners at the top of the internal equipment column, and the centers of two side panels (–X and –Y). We put a single-axis (Z) accelerometer on one of the bottom corners of the box structure. Figure 2 shows the accelerometer locations. The bottom of the separation ring was mounted to an aluminum test fixture, which was then bolted to the shaker table.

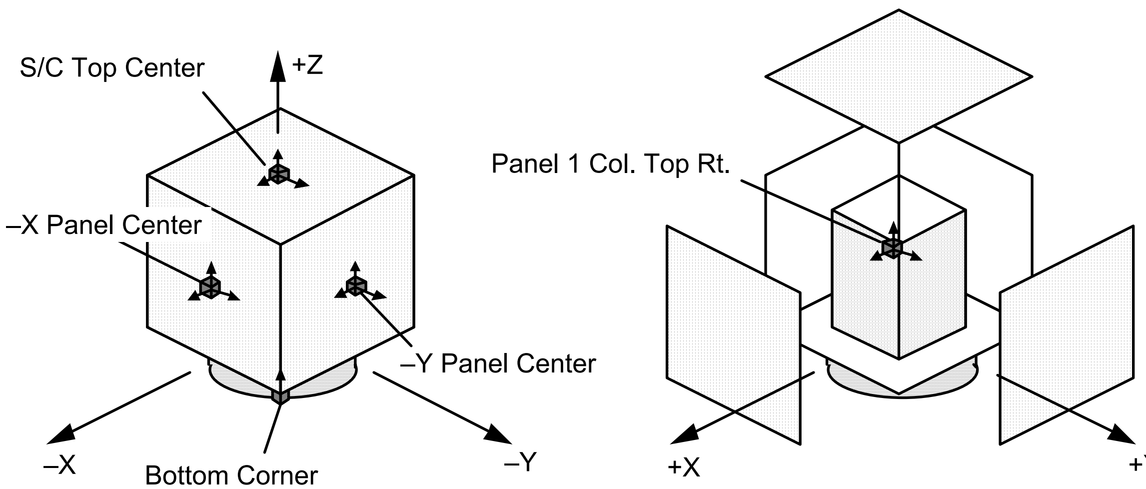

Fig. 2. Accelerometer Locations for the Engineering Model.

In each axis, the EM was tested in the following sequence:

- Low-level sine sweep from 20 to 2000 Hz to determine natural frequencies
- Random vibration, at incrementally higher levels to ensure the input matched the specified power spectral density (PSD) within acceptable tolerances, culminating at full qualification levels for one minute.
- Low-level sine sweep to ensure the dynamic characteristics had not significantly changed.
- Sine burst at 30 Hz, at incrementally higher levels until the full qual level (35 g) was reached.
- Low-level sine sweep.

Thermal vacuum testing was also performed, before the vibration testing.

5. Interpret test results and gain knowledge

   As explained above, the purpose of development testing was to gain knowledge that would help us design the flight structure. Of main interest was fundamental frequency, approximate mode shapes, response to random vibration, and whether the EM still operated after testing.

6. Develop a simple finite-element model.

   From the start, we planned not to be dependent on a detailed finite-element model. There were two reasons for this: First, the cadets did not have the necessary knowledge and would not have learned much by having a consultant generate such a model for them. Second, we believed such a model was not necessary and was not cost-effective for the design we envisioned.

Still, we planned to use the results of development testing to develop a simple, semi-correlated finite-element model, which we could then modify along with the evolving design to provide confidence. A simple model developed in this way would give us reasonably reliable predictions of fundamental frequency and response to random vibration as we modified the design.

7. Design the flight structure.

   Our plan for developing the final design was to continue to keep things as simple as possible, with the following process:

   - Keep load paths simple and use proven designs for joints. In other words, we planned to design a structure that we could analyze easily.
   - Use hand analysis to size the structure for strength requirements.
   - Plan how to satisfy fracture-control requirements and, if needed, modify the design accordingly.
   - Develop a simple finite-element model, using assumptions similar to those used for generating the semi-correlated model of the EM.
   - Predict modes of vibration and responses to specified random vibration; compare with targets and assumptions.
   - Iterate the design, as needed.

8. Build and test a qualification model (QM).

   In keeping with the philosophy of true qualification testing, the QM is being built at USAFA to the design intended for the flight unit and with the processes intended for the flight unit. As of the date of this paper, manufacturing of the QM has just begun. Qualification testing is planned for early February, 2002.

   Qualification random-vibration testing is our planned method of verifying fatigue life for the flight model. Fatigue life can't be verified by testing a flight unit because, after testing, the unit still must have enough fatigue life to make it through the mission. Testing a dedicated, nonflight unit to environments that are more severe and of longer duration than the flight unit will ever see does not prove the flight unit has adequate fatigue life, but it provides a great deal of confidence when both units are built to the same recipe. For FS2, we plan to test the QM to a random-vibration environment three decibels above the acceptance environment, for three minutes per axis. The flight unit will then be tested to acceptance levels at one minute per axis.

9. Interpret test results and gain knowledge.

   The schedule for building and testing the flight unit provides time, if necessary as a result of QM testing, to make minor modifications to the design. If any such design changes are necessary, we will first modify the QM and repeat qual testing.

10. Build and test the flight unit

    Testing of the flight unit is scheduled for April, 2002.

Results of Development Testing

The fundamental frequency for the EM was 182 Hz, for two identical modes in the X and Y axes. Based on relative accelerations measured at the instrument locations, we determined these were the rocking modes we had expected. The mode shapes apparently consisted of lateral acceleration at the c.g. combined with near-rigid-body rotation of the outer box structure. Most of the strain energy for this mode is in bending of the machined ribs in the baseplate. A simple finite-element model developed later in the program confirmed this assumed mode shape (Fig. 3).

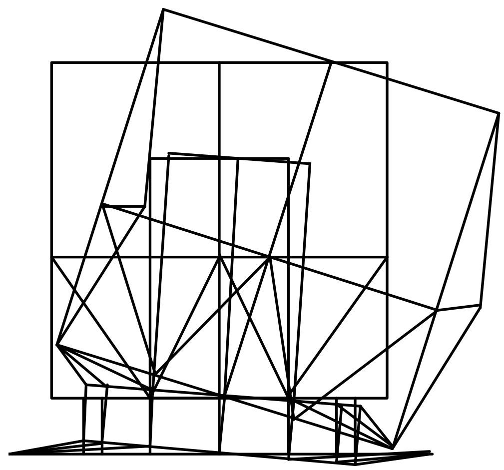

Fig. 3. Fundamental Rocking Mode of the Engineering Model. This finite-element model was correlated for the rocking mode to the extent possible with the limited test data. The figure shows that the internal column does not move much with this mode. Nearly all the strain energy is in bending of the baseplate. The baseplate does not bend much inside the adapter ring because it is a solid plate in this region, whereas it's machined outside the ring to leave a web and some 1/4"-thick ribs.

The surprising result of the EM test program was how much this rocking mode responded in the random-vibration test. The accelerometer at the top of the EM measured a root-mean-square (RMS) acceleration of 54 g, of which about 41 g RMS was associated with the rocking mode. The latter value was determined by numerically integrating the response PSD (Fig. 4) between 100 Hz and 240 Hz. The RMS acceleration from first-mode response is approximately the square root of the area under the curve in that frequency range.

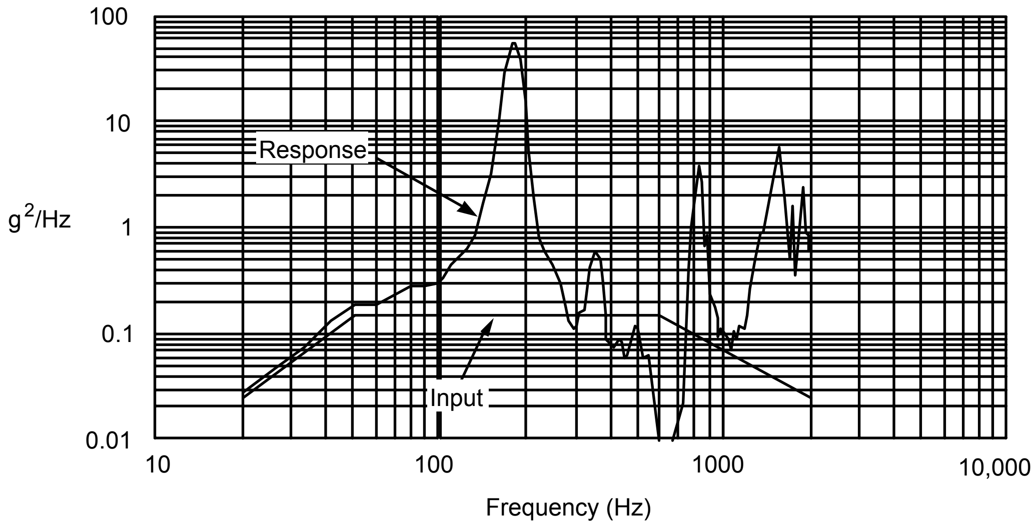

Fig. 4. Response PSD: X-axis Acceleration at the Top of the Engineering Model Measured during the X-axis Random-Vibration Test. This response is from testing at qualification levels. The large peak at 182 Hz indicates excitation of the fundamental rocking mode.

The RMS value is the standard deviation of random vibration. At three standard deviations (σ), the acceleration at the top of the box associated with the rocking mode was about 123 g. We immediately suspected such high excitation of this mode meant the 3-σ moment at the interface between the baseplate and the ring was considerably higher than that caused by the specified quasi-static loads.

Subsequent analysis confirmed this suspicion. As noted in Fig. 3, the internal column does not participate significantly in this mode, so we were able to estimate the moment at the baseplate/ring interface by accounting for motion only of the box, with its mounted equipment:

$$m_y = A_x wz + R_y I_y$$

where m_y is moment about the Y axis, A_x is the c.g. acceleration (in g's) in the X direction, w is the weight (lbs) of the box structure, z is the Z distance (in) from the c.g. to the bolt pattern, R_y is the angular acceleration (rad/s^2) about the Y axis, and I_y is the mass moment of inertia (in·lb·s^2) of the box structure about an axis passing through the c.g. and parallel to the Y axis. This equation results in a 3-σ moment that is about 2.7 times the moment caused by the 35-g design ultimate quasi-static load acting on the entire mass of FS2.

This information was quite surprising and quite valuable to the upcoming design of the flight unit. We now had two options:

1. Design the flight structure to be able to withstand the qualification-level accelerations measured in the development test.
2. Try to sell NASA/Goddard on the idea of notching the input PSD when testing the qualification and flight units to ensure the interface moment does not exceed the moment caused by the specified quasi-static loads.

The latter option arose based on our understanding that, because of limited energy, random vibration during flight does not cause much excitation of vibration modes that have much mass participation. In other words, random vibration should not drive the design of a payload's primary structure. On the other hand, an electrodynamic shaker controlled only by base acceleration has virtually unlimited energy and thus can excite a payload's fundamental frequency at high levels if that frequency is within the range of the input.

We explored with NASA the possibility of notching the input PSD, a strategy in which the input level is reduced near the fundamental frequency of the test article to prevent overtesting. However, it soon became apparent that the FS2 program did not have the budget to provide the analysis needed to quantifiably justify notching. The same was true for justifying force levels for force-limited vibration testing, another approach commonly used to make testing more realistic. Thus, in keeping with the program's philosophy, we opted to design the flight structure to withstand the un-notched PSD.

Development testing identified several goals for design of the flight structure:

- Reduce weight—Although weight was not critical, reducing weight from that of the EM, through a more efficient structure, would serve two purposes: reduce structural loads (forces and moments) for given acceleration and make the spacecraft easier to handle on the ground.
- Reduce the fundamental frequency—Doing so should lower the peak response of the rocking mode to base-driven random vibration. We wanted to stay above 50 Hz to keep structural verification as simple as possible. To account for uncertainty, we set a target of at least 80 Hz for design, based on prediction by a simple finite-element model.
- Increase damping—Raising the damping for the rocking mode would reduce its peak response to random vibration. Unfortunately, designing damping into the structure with viscoelastic materials was beyond our capability and budget. To simplify assembly, we wanted to reduce the number of bolts used in the EM to join the side walls of the box structure. Fewer bolts can still carry the flight and test loads and might lead to higher damping. Most structural damping comes from energy losses at joints, and we thought it reasonable that using fewer bolts (thus less total clamping force) might cause more energy loss. We didn't expect much damping increase here, but we thought it was a step in the right direction.

Design of the Flight Structure

As mentioned above, the key part of the structure is the baseplate. Its design influences the rocking mode most, and it will have the highest stresses in test and during launch. Reducing weight in the other five sides of the box, as we planned to do by making the structure more efficient, would tend to increase the fundamental frequency. We believed, however, that making the baseplate structure more efficient would more than compensate, resulting in a lower frequency while also reducing weight.

We decided to machine the baseplate out of 3/4”-thick 6061-T651 plate, which is low in cost, readily available, and resistant to corrosion. We also wanted a design with direct load paths and easily assessable strength, using classical “hand” analysis. Figure 5 shows the final design. The machined ribs act like beams to carry the inertia loads from the side panels to the bolts attaching the baseplate to the adapter ring, so we used beam theory to size them. We used an empirically based bathtub-fitting method of analysis to determine required web thicknesses in the pockets containing bolts. These webs bend as they shear the loads from the bolts to the ribs.

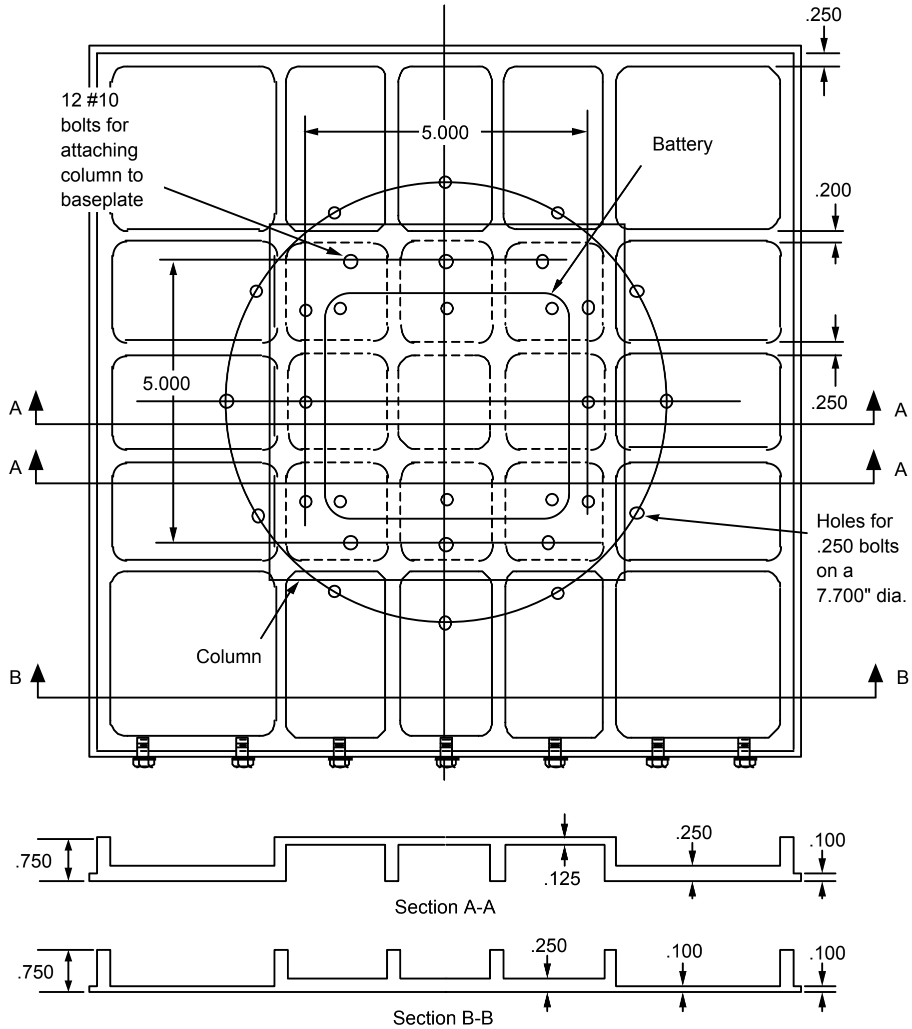

Fig. 5. **Design of the Flight Baseplate.** The plate is machined from both sides to provide interfaces for the column (top) and adapter ring (bottom). A battery mounts as shown inside the column. For clarity, not all dimensions are shown. The bolts shown along one edge are actually used for all four edges to attach the side panels of the box structure.

The design loads used for sizing the baseplate were derived from the 3-σ accelerations and mode shape determined from EM testing, at qualification levels of random vibration, and mass properties corresponding to the new design. We used factors of safety of 1.25 for ultimate and 1.0 for yield. NASA requires 1.4 ultimate and 1.1 yield for flight loads, but the driving event for the FS2 structure is qualification testing, so we decided lower factors of safety are appropriate.

To keep the frequency of the rocking mode as low as possible, we made the ribs no thicker than they need to be in order to carry the design loads (1% margin of safety for yield). Although such a low margin appears not to be in keeping with the program philosophy, we are confident in the baseplate's strength. Our finite-element model, revised to match the current design, predicts

– the rocking mode will drop from 182 Hz to about 120 Hz, and

– the response acceleration at the top of the box will drop from 41g to about 26g-RMS, based on the same damping (1.3%) as was needed to correlate the EM model.

The 1% margin of safety is based on the 41g measured in the EM test. Because of uncertainty, we decided not to base our analysis on the predicted 26g.

For a ductile material such as 6061-T651, the most likely failure during random-vibration testing is fatigue. A quick check shows the baseplate ribs should have enough fatigue life to make it through the three-minute test. The test itself, though, will be the true verification for fatigue life. If the QM makes it through qual testing, there will be little doubt the flight unit's structure will have enough fatigue life to withstand acceptance testing (one minute per axis, 3dB down) and launch.

We also refined the designs of the four side panels and the top panel, but, instead of analysis, the refinement was based on judgment, producibility, and good engineering practices. For example, the material under the bolts used to join panels was thinned down to 0.100" in order to make the attachments bearing critical rather than shear critical—a good practice for avoiding failure from uneven load distribution between fasteners. Knowing the side and top panels were not highly loaded, we thinned the machined ribs (also an orthogrid pattern) from 0.250" to 0.100", based on judgment. We kept the side panels 0.75" thick (rib height) so they would have enough bending stiffness to keep shear stresses low in the adhesive used to attach the solar panels (cells bonded to thin sandwich panels). Table 2 summarizes the reduction in structural weight of the six sides to the box for the flight model.

TABLE 2. Comparison of Structural Weight. The box structure for the flight model (FM) weighs about 9 lbs less than that for the engineering model (EM), a reduction of about 34%.

Part	EM Weight (lbs)	FM Weight (lbs)
Baseplate	7.6	5.5
Four side panels (total)	15.5	9.2
Top panel	3.2	2.6
Total	26.3	17.3

Work Yet to be Done

As of November, 2001, we are presently machining the parts for the QM, with qualification testing planned for early February, 2002. Between now and then, we will assess each part of the spacecraft for NASA's fracture-control requirements. Throughout design, we did spot checks to provide confidence that we'll be able to show each part to be either fail-safe or low-risk. Abbreviated definitions of these categories are as follows: A *fail-safe part* is one that can fail from crack growth without causing the rest of the structure to fail under limit loads. *A low-risk part* is one that has little stress and is made of a well-controlled material. A *low-risk threaded fastener* is one that is fail-safe, is made of a ductile material by an approved vendor, is preloaded to ensure no gapping at limit load, and has an effective locking feature. (See NASA-STD-5003 for precise definitions.) The Phase 0/1 Safety Panel Review at NASA/JSC is scheduled for early December of this year.

Another planned activity is to develop processes for tapping holes and installing inserts at USAFA. We plan to do pull-out tests to demonstrate the processes. An in-house certification process will ensure that anyone performing these operations on flight hardware will first do so with test coupons that subsequently pass the pull-out test criteria.

Summary and Conclusions

Development testing proved well worth the time and expense. Without it, we would not have recognized that random-vibration testing would present the highest loads to the primary structure. We would have designed for the specified quasi-static loads, which were less than half as severe as qualification-level random vibration, and thus would have had significant risk of structural failure in test. Finite-element analysis could have provided a predicted response to random vibration, but, without a good estimate of structural damping, such analysis would have been highly uncertain.

We are convinced that the most cost-effective approach to developing space-mission structures is to use testing as a means of gaining information incrementally through the program rather than to base confidence solely on analysis.

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Author Biography

Tom Sarafin, as President of Instar Engineering and Consulting, teaches short courses and provides advice and services to space programs in the areas of requirements definition, verification planning, structural design and analysis, launch environments, quality, and risk assessment. He has over 22 years experience in the space industry, including nearly 14 years at Martin Marietta Astronautics (now Lockheed Martin), where he contributed to and led activities in structural analysis, design, and test. He is the editor and principal author of the book *Spacecraft Structures and Mechanisms: From Concept to Launch*. He's also a contributing author to *Space Mission Analysis and Design* (all three editions) and *Human Spaceflight: Mission Analysis and Design*. He has recently been writing and distributing a series of articles called "Doing Things Right in Space Programs." He has a bachelor's degree in civil engineering from The Ohio State University.