Small Satellite Research Center
United States Air Force Academy

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FRACTURE CONTROL COMPLIANCE REPORT

FALCONSAT-2

Small Satellite Research Center
Department of Astronautics
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REVISIONS

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EXECUTIVE SUMMARY

FalconSat-2, a small satellite scheduled for launch with the Space Transportation System, satisfies the fracture-control requirements of NASA STD-5003. The satellite contains no fracture-critical parts. All parts satisfy the criteria for being either exempt from fracture control, fail-safe and contained, or low-risk fracture parts. With qualification and acceptance testing successfully completed, FalconSat-2 should be structurally safe to fly based on the combined conclusions drawn herein and in the Structural Verification Report.

FalconSat-2 is the third in a series being developed in a small-satellite program at the United States Air Force Academy, following FalconGold and FalconSat-1, and is the first of the series to be launched aboard the Space Shuttle. The purpose of this program is to teach cadets by getting them involved in real space missions. Dr. Jerry Sellers is program manager.

Fracture control for FalconSat-2 was the responsibility of Dr. Ron Humble, Chief Engineer for the FalconSat program, and Mr. Tom Sarafin, a consultant to the program. Between them, they have 45 years experience in the space industry.

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1. SCOPE AND PURPOSE

This report documents how the FalconSat-2 (FS-2) program at the United States Air Force Academy (USAFA) has satisfied the fracture-control requirements specified in NASA-STD-5003, according to the FalconSat-2 Fracture Control Plan.

2. APPLICABLE DOCUMENTS

The documents listed below apply to this report to the extent specified herein.

- GSFC 541-PG-8072.1.2 "Fastener Integrity Requirements."
- MSFC-STD-3029, May 2000. "Design Criteria for Controlling Stress Corrosion Cracking."
- NASA-STD-5003, October 7, 1996. "Fracture Control Requirements for Payloads Using the Space Shuttle."
- USAFA-FS2-FCP-1, 12/3/01. FalconSat-2 Fracture Control Plan.
- USAFA-FS2-SVR, May, 2002. FalconSat-2 Structural Verification Report.

3. DESCRIPTION OF THE FALCONSAT-2 STRUCTURE

The FS-2 structure consists of a nearly cubic box, approximately twelve inches per side. The six walls are made of 6061-T651 aluminum plate, machined in orthogrid patterns, and are attached with threaded fasteners. Solar arrays are bonded and bolted to the four side walls, and the top wall supports the Miniature Electrostatic Analyzer (MESA) instruments, two small antennas, and a lug for ground handling. A four-sided column, with each side machined from 6061-T651 aluminum plate, is used to support the rest of the FS-2 equipment. The column bolts to the box's base plate, which in turn bolts to an adapter ring. This ring provides the interface to the PES, attaching with a Marmon band. Figure 1 shows the structural configuration.

All structural parts, with the exception of the adapter ring, were fabricated by machining at USAFA. GSFC made the ring out of an aluminum alloy with high resistance to stress-corrosion cracking.

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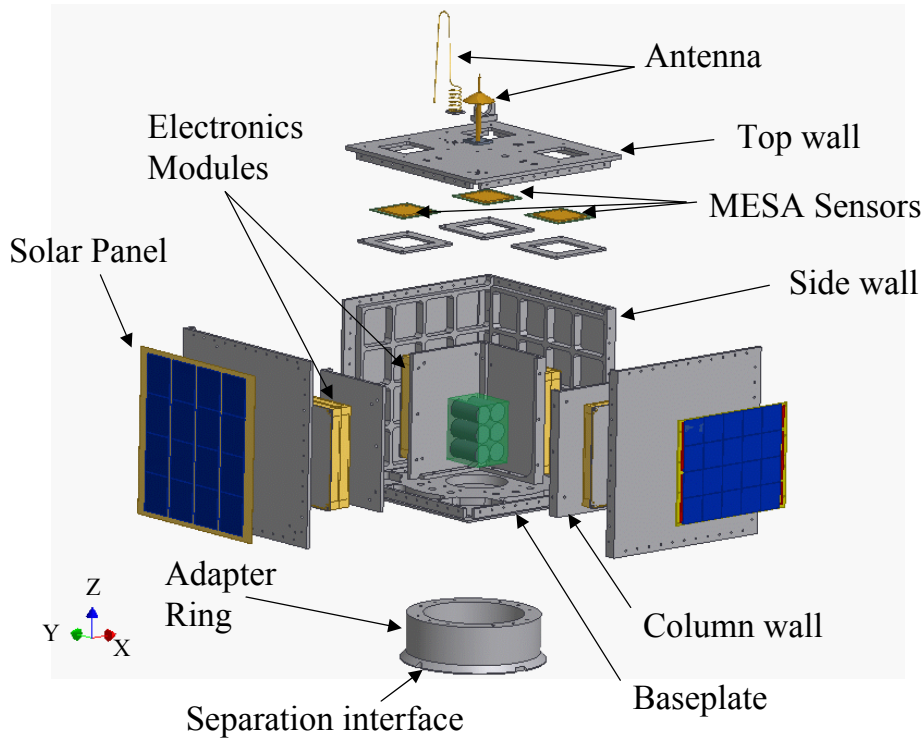

Figure 1: FalconSAT-2 Structural Configuration.

4. FRACTURE CONTROL APPROACH AND CRITERIA

Our strategy for satisfying the fracture-control requirements of NASA-STD-5003 has been to design the FS-2 structural parts (all parts that are not exempt from fracture control) to be either fail-safe and contained or low risk. Per Sec. 1.3c of NASA-STD-5003, parts that are exempt from fracture control are those that are clearly nonstructural and not susceptible to crack propagation. Examples of exempt parts are thermal blankets, electrical cables, and parts solely under compressive loading, such as washers.

The main criterion for a part to be considered fail-safe is that—if it had a crack in the worst possible location and orientation, and if that crack were to grow until either the part fails or the crack is stopped by some feature of the part—analysis must show the remaining structure would still be able to withstand limit loads. An additional criterion for a part to be considered fail-safe is that analysis must show that, in event of any single fracture failure, the structural assembly would still have a fundamental frequency greater than 50 Hz and thus would not couple with the Orbiter structure to cause high loads.

Normally, for a part to be acceptable under the fail-safe classification, it also either must be contained, which means no piece of the failed part would be able to escape into the Orbiter's cargo bay, or must have low release mass, which means the failed piece that is not contained would weigh no more than 0.25 lb. For Hitchhiker (HH) canister payloads that are mounted to

the pallet ejection system (PES) and that are intended to jettison from the canister during the mission, such as FS-2, a part of any size must be contained to be acceptable as a fail-safe part because even a part that has low release mass might jam the PES.

A structural part is also acceptable if analysis shows it to be a low-risk fracture part. Section 4.1 defines criteria for this classification when applied to structural parts other than fasteners. Section 4.2 provides our interpretation of the low-risk classification for fasteners, as defined in Sec. 4.2.2.4.3 of NASA-STD-5003.

As a result of this design approach, our plan has been to have no fracture-critical parts. According to our interpretation of NASA-STD-5003, a fracture-critical part, which is one that is neither fail-safe and contained nor low risk, must receive nondestructive evaluation to establish a maximum crack size and safe-life analysis to show a crack of that size would not cause catastrophic failure.

4.1 Structural Parts Other than Fasteners

A structural part is either fail-safe and contained (per the above criteria), low risk, or fracture critical. Any structural part that is not a fastener is considered *low risk* if all of the following conditions are satisfied:

- The part is not part of a pressure vessel or pressurized system.
- The limit tensile stress does not exceed 30% of the allowable ultimate tensile stress.
- The part is made of a ductile metal alloy that is not sensitive to stress-corrosion cracking, per MSFC-STD-3029, that has relatively high fracture toughness, and that is made according to applicable military specifications.
- The part is made with a process that does not tend to cause cracks.
- The part passes a visual inspection for cracks at the part level.
- The part will not be subjected to any more fatigue damage than is incurred by acceptance testing, transportation, and a single mission.

All nonexempt parts that fail to meet the criteria for fail-safe and contained or low risk will be considered *fracture critical*. Any such parts will be inspected with a reliable method of non-destructive evaluation. That inspection will be used to establish a maximum size of crack, and then safe-life analysis must show the part can withstand four times the expected number of loading cycles without failure.

4.2 Fasteners

Fasteners used in the FS-2 structure include bolts (and screws), washers, nuts, and threaded inserts. Only the material in the bolts will see tension, so only the bolts are of concern for fracture, with the others being exempt from fracture control. The FS-2 approach has been to show all bolts used in structural applications (meaning they will be loaded significantly in flight) either are fail-safe and contained or meet the criteria for low risk specified in Section 4.2.2.4.3 of NASA-STD-5003. As such, no dedicated method of containing fastener heads is required. All lightly loaded fasteners, such as those attaching electrical connectors, are contained with RTV (an epoxy suitable for space applications).

According to Sec. 4.2.2.4.3 of NASA-STD-5003, for a fastener to be classified as a low-risk fracture part, fracture of the fastener would not result in a single-point catastrophic failure, and the fastener must meet the following requirements:

a. Be a high-quality military standard, national aircraft standard, or equivalent commercial fastener that is fabricated and inspected in accordance with aerospace-type specifications. If the fastener will be loaded significantly in tension, it shall have rolled threads meeting aerospace or equivalent rigorous standards.

b. Be fabricated from well-characterized metal that is not sensitive to stress-corrosion cracking. If the bolt is used in a tension application, it shall not be made of an alloy with low fracture toughness, as defined in Sec. 3.27 of NASA-STD-5003, or, specifically, Ti-6Al-4V STA titanium.

c. Acquire during installation a preload that is high enough to prevent gapping so that cyclic stress in the bolt material is limited.

d. Have an effective locking feature for ensuring the preload needed to prevent gapping is maintained during flight.

5. STATUS OF COMPLIANCE FOR FRACTURE CONTROL

Sections 5.1 and 5.2 summarize compliance for structural parts and fasteners, respectively. Appendix A documents supporting analysis. Additional confidence is provided by the FS-2 test program, which included qualification vibration testing of a flight-like Qualification Model (QM) (February 2002), acceptance vibration testing of the Flight Model (FM) (July 2002), and qualification and acceptance vibration testing of the S-band antenna[1].

5.1 Parts Other than Fasteners

Table 1 summarizes compliance for parts other than fasteners. Parts that are obviously exempt from fracture control, such as washers and electrical wires, have been omitted from the list. Rationale for the classification shown in Table 1 is either judgment or the analysis documented in Appendix A, depending on the part.

[1] As explained in the Structural Verification Report, the S-band antenna has been redesigned twice, once following fatigue failure in QM testing and another time after solder cracks developed in FM testing. Qualification and flight models of the final S-band design have been successfully tested for qualification and acceptance random vibration, respectively (September 2002).

Table 1: Parts Classification

Drawing No.	Part No.	Description	Qty	Fail Safe and Contained	Low Risk	Exempt	Fracture Critical
#200100		Top-level assembly	1				
#200126		Module installation	1				
#200128		MIB assy	1	x			
#200130		MIB PWA	1			x	
#200131		MIB PCB	1			x	
PCA/PE009C/V01		Power module assy	1	x			
PCA/TE005A/F		SIM module assy	1	x			
PCA/OE015B		OBC module assy	1	x			
PCA/RE071A/V01		Receive module assy	1	x			
PCA/RE093A		Transmit module assy	1	x			
#200127	–001	Module box lid	5			x	
#200101		Base plate integration	1				
#200102	–001	Base plate	1	x			
#200103	–500	Column wall	1	x			
#200103	–501	Column wall	3	x			
#200105	–500	Sep switch assy	1				
#200106	–001	Switch mounting bracket	1	x			
#1HE1	–6	Separation switch	5			x	
#200107		Sun sensor assy	1				
#200108	–500	Sun sensor bracket	1			x	
#200132	–500	Sun sensors PWA	1			x	
#200133	–001	Sun sensor PCB	1			x	
GD1556059		Interface ring	1	(up to GSFC)			
#00348	–ASY1	Battery assy	1	x			
#200109		Harness assembly	1				
#200111		Top panel integration	1				
#200112	–500	Top panel assy	1				
#200112	–001	Top panel	1		x		
#200113	–500	MESA sensor/LA	2				
#200137		MESA PWA	1			x	
#200138		MESA PCB	1			x	
#200139		Top aperture plate	1			x	
#200140		Middle aperture plate	3			x	
#200141		MESA bottom plate	6			x	
#200142		Thin Teflon insulator sheet	2			x	
#200143		Thick Teflon insulator sheet	1			x	
#200114	–500	MESA sensor/RPA	1				
#200137		MESA PWA	1			x	
#200138		MESA PCB	1			x	
#200144		PRPA screen holder plate--top	4			x	
#200145		Thick Teflon RPA spacer	2			x	
#200115	–500	MESA clamp	3			x	
#200107	–500	Sun sensor assy	1				
#200108		Sun sensor bracket	1			x	

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#200132		Sun sensor PWA	1			x	
#200133		Sun sensor PCB	1			x	
#200118	–500	Handling lug assy	1				
#200118	–001	Handling lug	1		x		
FS-VHF-1		VHF antenna	1		x*		
FS-SB-1		S-band antenna	1		x**		
FS-VHF-2		Tuning box	1	x			
#200120		Side panel integration--side 1, 3	2				
#200121	–500	Side panel assy/USAFA	1				
#200121	–001	Side panel	1		x		
#200134	–500	Solar array PWA	1				
#200135		Solar array PCB	1	x			
#200124		Side panel integration--side 2, 4	2				
#200125	–500	Side panel assy/Spacequest	1				
#200125	–002	Side panel	1		x		
XYZ SP-9		Spacequest solar panel	1	x			

Notes for Table 1:

*The VHF command antenna is a wire whip made of silver-plated brass. The diameter is so small that a significant crack (miniscule in this case) could not be detected by nondestructive inspection. Because it is cantilevered, it would not be contained in event of fracture failure. The flight antenna received acceptance testing for random vibration as part of the FM assembly. In this test, the antenna's fundamental bending mode was not noticeably excited, as it is quite low in frequency. The second mode was visibly excited, but not enough to have caused much stress in the wire. The VHF antenna is a low-risk fracture part because its limit stress is less than 30% of its material's ultimate stress, the material, and the material is not subject to stress corrosion cracking because a cantilevered wire has no sustained stress.

**The post and bolt flange of the S-band antenna were machined from a single piece of brace and then silver plated. A dedicated, nonflight antenna passed qualification vibration testing for three minutes per axis, and the flight antenna passed acceptance-level random vibration testing. This antenna is considered low risk because the limit stress is less than 30% of the material's ultimate stress, the material is ductile, and the material is not subject to stress corrosion cracking.

5.2 Fasteners

All bolts used in FS-2 for structural applications are high-quality military-standard fasteners with rolled threads, procured from NASA GSFC in accordance with GSFC 541-PG-8072.1.2. The bolts are made of A-286 material, which is ductile, is highly resistant to stress-corrosion cracking, and has good fracture toughness. All bolts used for the primary structure are size #10 or greater. To minimize cyclic stress, the bolts have been preloaded sufficiently at installation to ensure joints do not gap at limit load (see SVR Appendix B), thus minimizing cyclic stress in the bolt. All fasteners have locking features that will prevent relative rotation and loss of preload.

If any fastener in any fastener pattern were to fail, the remaining fasteners and structure could still withstand limit loads without catastrophic failure. This statement is based on judgment for some fasteners and the analysis documented in Appendix A for the fasteners that are most highly loaded.

If any fastener were to fail, the structural assembly would still have a fundamental frequency greater than 50 Hz to ensure FS-2 will not modally couple with the Orbiter's structure to cause

high loads. This statement is based on a combination of judgment and, indirectly, the analysis in Appendix A. The fundamental frequency, as determined in vibration testing of the FS-2 Qualification Model, is 157 Hz. None of the potential crack-growth failures considered in Appendix A would cause the fundamental frequency to fall below 50 Hz.

Fasteners internal to FS-2 are classified as "fail-safe and contained." Fasteners that are not contained within FS-2 are "low-risk fracture parts," per the criteria defined in Sec. 4.2. All bolts and screws have locking features. The tiny screws used to attach connectors and small components are locked with RTV; the larger fasteners, which will carry significant loads, are locked either with self-locking nuts or Spiralock inserts. Table 2 summarizes compliance for fasteners.

Table 2: Fastener Classification

Drawing No.	Description	Bolt Size	Locking Feature	Install Torque (in-lb)	Fail Safe and Contained	Low Risk	Fracture Critical
#2000 00	Top-level assembly						
	Bolts attaching the six walls	#10	Spiralock	60 ± 3		x	
#200026	Module installation						
	Bolts attaching modules to column	#10	Spiralock	40 ± 3		x	
#200028	MIB module assy						
	Screws	M4			x		
#200101	Base plate integration						
	Bolts attaching base plate to ring	1/4	Nut	100 ± 3		x	
	Bolts attaching column walls	#10	Spiralock	60 ± 3		x	
	Bolts attaching column to base	#10	Spiralock	60 ± 3		x	
	Bolts attaching battery to base	#10	Nut	60 ± 3		x	
	Bolts attaching switch stand	#10	Spiralock	60 ± 3		x	
#200007	Sun sensor assy						
	Bolts	#6	Nut	16 ± 2		x	
#00348	Battery assy						
	Bolts attaching battery to plate	M5			x		
#200009	Harness installation						
	Phillips-head screw	#4	RTV	9 ± 2	x		
	Slot-head screw	#4	RTV	9 ± 2	x		
#200111	Top panel integration						
	Bolts attaching the MESA sensors	#10	Nut	Snug		x*	
	Bolts attaching handling lug	#10	Spiralock	60 ± 3		x	
	Screws attaching S-band antenna	#4	Nut	9 ± 2		x	
	Screws attaching VHF antenna	#4	RTV	9 ± 2	x		
	Vent hole fastener	#4	Nut	9 ± 2		x	
#200013	MESA sensor/LA						
	Screws	#0	RTV		x		
#200014	MESA sensor/RPA						
	Screws	#0	RTV		x		
#200015	MESA clamp						
#200007	Sun sensor assy						
	Bolts	#6	Nut	16 ± 2		x	

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#200120	Side panel integration--side 1, 3						
	Screws attaching USAFA panel	#6	Nut	Snug		x**	
#200124	Side panel integration--side 2, 4						
	Screws attaching SpaceQst panel	#6	Nut	Snug		x**	

Notes for Table 2:

*The MESA sensors are attached to the structure with eight #10 bolts each. These bolts are torqued lightly because the sensor substrate is non-metallic, so there is little preload. Each sensor assembly weighs about 0.25 lb, and there are 8 bolts per sensor. Even if the sensor sees 1000 g's acceleration in response to random vibration during launch, the bolt load is 250 lb divided by 8 bolts, or 31 lb per bolt. This is negligible cyclic stress on a bolt that can lift a car (3200 lb allowable tensile load). We believe these bolts fit in the "low-risk" category for fracture control.

**The #6 alignment screws attaching the solar panels to the side walls are installed with a low torque to ensure the non-metallic solar panels will not be crushed. These bolts will be under near-zero stress during launch because the adhesive bond is the primary load path (and is the stiffer load path). A screw will be significantly loaded only if the bond fails. As with everything else on FalconSat-2, the adhesive bond has been qualified (all four panels were present during qualification vibration testing) and all the bonds on the flight model will receive acceptance vibration testing. If an undetected debond occurs during acceptance testing and propagates to total bond failure in flight, the four #6 bolts must carry the full load from the solar panel. The solar panel weighs 1.78 lb. In the qualification vibration test, at acceptance levels, an accelerometer mounted in the middle of a side panel showed a 3-sigma load of about 100 g. Thus, the total cyclic load on a bolt would be 100(1.78)/4 = 45 lb. The bolt is made of 160-ksi A-286 and has an allowable ultimate tensile load of 1620 lb. In conclusion, even if the bond were to fail, the cyclic stress in the bolts would be insignificant, and the chance of bolt failure would be negligible. Thus, we consider the screws to be acceptable under the classification of low risk.

6. SUMMARY AND CONCLUSIONS

FalconSat-2 satisfies the fracture-control requirements of NASA STD 5003.

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