

Fracture Control for satellite programmes - a critical review

ESTEC Fracture Control Workshop, Feb. 2009

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All the space you need



Quote from top level ECSS standard
ECSS-S-ST-00C (July 2008) :

ECSS system objectives and policy

The overall objectives of using the ECSS system of standards include:

- **“Achieving more cost effective space programmes and projects in Europe”**
- reducing risk and guarantee interoperability and interface compatibility by applying proved and recognized requirements and methods.

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Causes for in-flight failure of satellites

- Launcher failures
- Power system design errors
- AOCS sensors/actuators malfunctioning
- Propulsion system malfunctioning
- AIT mishaps: Forgotten Red Tags, harness failures
- Ground Control Operator errors
- ➔ No known satellite losses due to structural failure

- Structural failures occur sometimes during ground testing
 - Shaker malfunctions
 - Operator errors
 - Engineering errors

Comparison of Fracture Control standards (1)

NASA standards:

- NASA-STD-5003 (Oct.1996): “FC reqt’s for Shuttle Payloads”
 - Applicable to all Space Shuttle payloads
 - To preclude catastrophic failure
- NASA-STD-5019 (Jan.2008): “FC reqt’s for Spaceflight h/w”
 - Applicable to all human-rated space systems
 - To preclude catastrophic failure
- MSFC-RQMT-3479 (Jun.2006): “FC reqt’s for Composite and Bonded Vehicle and Payload Structures”
 - Specific requirements for composite structures
 - Introduces “Damage Threat Assessment”

Comparison of Fracture Control standards (2)

NASA standards (cont):

- Only human-rated systems are addressed – not unmanned systems or their GSE
- Only catastrophic failure scenario is addressed (loss of lives, ISS, Space Shuttle or major injury of crew)
- Independent Fracture Control Board exists. Fracture Control reviews are part of Safety review system

Comparison of Fracture Control standards (3)

ECSS standards:

- ECSS-E-30-01A (Apr.1999):
“Space Engineering: Fracture Control”
 - Introduced “Reduced FC” for single-mission, unmanned programs, now obsolete
- ECSS-E-ST-32-01C (Nov.2008):
“Space Engineering: Fracture Control”
 - To prevent catastrophic and critical failures
 - Critical hazard as per ECSS-Q-ST-40B definition:
“Major damage to flight system”
 - For satellites this is commonly interpreted as “Loss of mission”

Comparison of Fracture Control standards (4)

ECSS standards (cont.):

- Significantly broader scope:
 - Human-rated and unmanned systems are addressed
 - Critical hazard category also included
- No independent Fracture Control Board exists.
FC reviews are part of normal project reviews
- ➔ Objective not only human safety but also reliability

- Relation to ECSS-ST-32C not fully consistent
 - E.g. load enhancement factor 1.15 on SL and FS analyses
 - E.g. safety factor 2.5 on MDP instead of 2.0

New tasks triggered by ECSS-E-32-01C

- GSE directly interfacing to flight hardware is now subject to fracture control procedures
- Structural screening now includes metallic structures with $\sigma_L > 0.5 \sigma_y$
- Composite structures: full scope of §8.4 applies, i.e. no simplification compared to manned multi-mission vessels

What is the impact for satellites? (1)

- ECSS guidelines typically apply to ESA Science and Earth Observation satellites programs
- Typical structural characteristics of such programs:
 - CFRP sandwich primary structure
 - Aluminium or CFRP sandwich panels for equipments
 - Thermally stable CFRP structures (telescopes, optical benches)
 - Often with isostatic mounting principles
- Typical programmatic constraints:
 - Specifically developed or adapted structures
 - Short development cycles
 - Increasingly using Protoflight Model approach

What is the impact for satellites? (2)

- Composite structures (§8.4): What is required?
 - Defect Assessment (8.4.2)
 - **8.4.2.1.a:** The request to establish the maximum acceptable defect size is will inevitably end up in arbitrary definitions, since the damage propagation cannot be modelled accurately
 - **8.4.2.1.b:** The request to be able to detect the damage by NDI is unrealistic, since state-of-the-art NDI is not capable to clearly indicate and distinguish defects typology and sizes
 - **8.4.2.1.c:** It is not clear how the influence of the manufacturing defects on the structural integrity shall be verified, see point a.
 - **8.4.2.1.d:** “Acceptance criteria based on a fracture control methodology shall be established”
 - In the authors opinion, the methodology required for the tasks above does not exist (yet).
 - Bits and pieces of theory exist (interlaminar fracture), but no established calculation methods or codes.

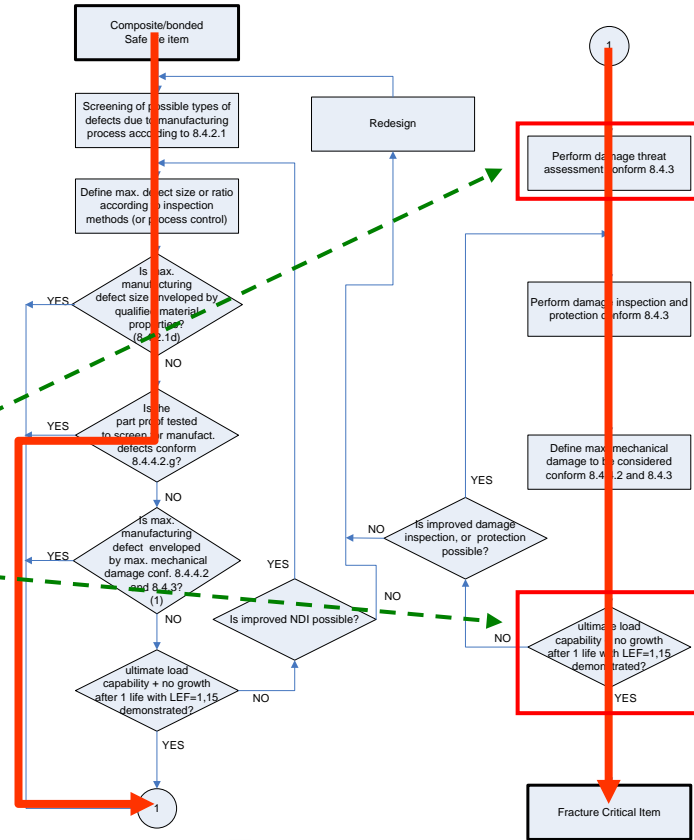
What is the impact for satellites? (3)

- Composite structures (§8.4): What is required?
 - Damage Threat Assessment (8.4.3)
 - **8.4.3.2.d:** “For the type and maximum magnitude of the threat during each event that can cause mechanical damage the resulting mechanical damage shall be identified with its type and size or level.”
 - Note: DTA required also for Low-Risk items
 - **Again, methodology does not exist for this task**
 - Compliance Procedures (8.4.4)
 - **8.4.4.2.b-f:** Dedicated sample test programs are stipulated with the aim to demonstrate Safe Life over the service life. Test parts must contain flaws relevant for all identified defect types.
 - **This approach may be suitable for a multi-million Euro, several years duration fundamental research programme, but is completely unsuitable for a "normal" satellite development project.**

What is the impact for satellites? (4)

■ The Proof Test Backdoor:

- 8.4.4.2.g allows verification per proof test at $1.2 * \text{limit load}$
- Due to lack of realistic alternatives, projects will choose this option
- Activities still required are:
 - Damage Threat Assessment 8.4.3
 - Demonstration as per 8.4.4.2.e of
 - Ultimate load capability
 - No growth after 1 life with LEF=1.15
 - If the author understands the chart correctly, scale or sub-scale tests with coupons containing flaws are required



(1) Only in the case where the manufacturing defect type is comparable to the mechanical damage considered at 8.4.4.2 and 8.4.3 (i.e. delamination and impact damage, but not e.g. porosity)

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What is the impact for satellites? (5)

- How to implement the FC sample testing?
 - Structure design must be sufficiently mature to allow definition of the FC sample → as minimum, PDR status is required for Structure Subcontractor
 - Manufacturing release for FM structure at CDR will require successful FC sample testing
 - Typical project durations: 6-9 months Phase C for Structure Subco
 - Rough estimate of FC tasks duration:
 - Assumption: Sample definition ready at PDR
 - Manufacturing of samples and test jigs, NDI: 4 months
 - Testing incl. intermediate and post-test NDI: 3 months
 - Analytical post-processing and safe-life verification: 4 months
 - Reporting, CDR data package processing: 1.5 months→ About one year duration
- Conclusion: Full scope of activities is not feasible due to schedule constraints

What is the added value for composites? (1)

- **Already existing tasks related to structural reliability**
 - Normal project reviews (SRR, PDR, CDR, QR, FAR)
 - Risk register process
 - Hazard Analysis
 - Single Point Failure Analysis
 - Reliability / Availability Analysis
 - Critical Items List
 - Failure Modes Effects and Criticality Analysis (FMECA)
 - Material selection based on SCC susceptibility

What is the added value for composites? (2)

■ Acceptance testing / workmanship verification

- All composite structures are manufactured under approved & controlled processes incl. material witness sample tests
 - All composite structures are inspected visually and by NDI
 - Composite acceptance tests at 1.0 times the limit load are defined already in ECSS-E-ST-32C
 - All satellites are acceptance tested on system level
 - Acceptance test loads are at least at limit load level
- ➔ Correct build-standard is verified by tests already defined
- ➔ The author is not aware of any structural in-flight failures which were caused by poor workmanship

What is the added value for GSE?

Typical sizing requirements for MGSE

- Safety critical GSE is sized with safety factor $SF_y = 3$ against yield and $SF_u = 4$ against ultimate failure → low stress levels
- Proof testing at 2.0 SWL is mandatory
- Typical fatigue load events for GSE $\ll 1000$ uses

Consequences for crack propagation

- Parametric ESACRACK analyses for typical hoisting device materials, parts dimensions and crack geometries were performed
- Due to the low stress, SIF is under or close to the threshold for crack propagation
- Critical crack size reached after several million load cycles
- ➔ MGSE safety already implicitly verified (for current SF's)
- ➔ For higher stress levels in GSE, this approach makes sense (operator safety)

What is the added value for Safe Life metallic structures?

- Low fatigue life (only environmental tests & one launch event)
 - Raw material is typically ordered with EN10204 standard 3.1B certificate, which includes NDI inspection
 - Most structures are sized for stiffness, which results in moderate stress levels
 - From experience, in the short fatigue life, defects do not grow to critical size
- ➔ Additional analysis work for little added value; however no principal problem for application
- ➔ Reduction to single point of failure as per “Note 2” makes sense. Relevance still seen as critical

Discussion & conclusions

- ECCS-E-ST-32-01C requires verification tasks for composites, for which the methodology does not exist
- ECCS-E-ST-32-01C still addresses critical hazard category
- The standard is too complicated and ambiguous
- SL composite structures are by definition Fracture Critical Items
- For satellite applications the standard adds significant activities with little added value
- Cost & schedule impact not justified

- The author recommends to rework the standard or at least to revise it for the Reduced FC (§11) for composite structures (e.g. revert to ECSS-E-30-01A)
- Precise contractual agreements are needed prior to project start to clearly define the scope of FC tasks