Вестник РУДН. Серия: Инженерные исследования
RUDN Journal of Engineering Research

2025;26(2):127–134

ISSN 2312-8143 (Print); ISSN 2312-8151 (Online)
journals.rudn.ru/engineering-researches

DOI: 10.22363/2312-8143-2025-26-2-127-134
EDN: LHUQMC

Research article / Научная статья

Analytical Review of the Common Failures of Satellite Structures: Causes, Effects, and Mitigation Strategies

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Article history
Received: January 17, 2025
Revised: March 15, 2025
Accepted: March 27, 2025

Conflicts of interest
The authors declare that there is no conflict of interest.

Abstract. Satellite structures are subjected to extreme conditions throughout their operational lifespan, including high launch loads, thermal cycling, and space debris impacts, making them vulnerable to structural failures. Understanding the causes, effects, and mitigation strategies for such failures is crucial for enhancing satellite reliability and mission success. This review critically examines the common structural failures in satellites, categorizing them by affected components such as primary frames, joints, thermal shielding, and deployable mechanisms. The study employs a comprehensive analysis of historical and recent failures, integrating insights from case studies, experimental research, and advancements in materials science and structural health monitoring. The findings highlight key failure mechanisms, including material fatigue, vibrational stresses, and thermal degradation, and assess innovative solutions such as smart materials and in-orbit repair techniques. By synthesizing current research and industry practices, this review provides a systematic understanding of failure trends and proposes future directions for improving satellite structural resilience. The insights presented in this study aim to support the development of more robust satellite architectures, ultimately contributing to safer and more reliable space missions.

Keywords: structural failures, failure mechanisms, materials science, health monitoring, risk mitigation strategies

Authors' contribution

Reza Kashyzadeh K. — introduction, general overview, section 3, 5, 6, and conclusion, writing the text; *Kupreev S.A., Samusenko O.E.* — analysis and scientific study of materials, section 2, 3 and 4.

Funding

This paper has been supported by the Ministry of Science and Higher Education of the Russian Federation under Agreement No. FSSF-2024-0005.

Data availability statement

The datasets can be made available upon request.

For citation

Reza Kashyzadeh K, Kupreev SA, Samusenko OE. Analytical review on the common failures of satellite structures: causes, effects, and mitigation strategies. *RUDN Journal of Engineering Research.* 2025;26(2):127–134. http://doi.org/10.22363/2312-8143-2025-26-2-127-134

Аналитический обзор распространенных отказов спутниковых конструкций: причины, последствия и стратегии смягчения последствий

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История статьи

Поступила в редакцию: 17 января 2025 г.
Доработана: 15 марта 2025 г.
Принята к публикации: 27 марта 2025 г.

Заявление о конфликте интересов

Авторы заявляют об отсутствии конфликта интересов.

Аннотация. Спутниковые конструкции подвергаются экстремальным условиям на протяжении всего срока их эксплуатации, включая высокие нагрузки при запуске, тепловые циклы и удары космического мусора, что делает их уязвимыми к структурным отказам. Понимание причин, последствий и стратегий снижения риска таких отказов имеет решающее значение для повышения надежности спутников и успешности миссий. В данном обзоре критически рассматриваются распространенные структурные отказы спутников, классифицируемые по пораженным компонентам, таким как основные каркасы, соединения, тепловая защита и развертываемые механизмы. В исследовании проводится всесторонний анализ исторических и современных отказов с интеграцией данных из тематических исследований, экспериментальных исследований, а также достижений в области материаловедения и мониторинга структурной целостности. Полученные результаты выявляют основные механизмы отказов, включая усталость материалов, вибрационные нагрузки и тепловую деградацию, а также дают оценку инновационным решениям, таким как умные материалы и технологии ремонта на орбите. Обобщая современные исследования и практики отрасли, авторы систематизируют тенденции отказов и предлагают перспективные направления для повышения устойчивости спутниковых конструкций. Результаты исследования направлены на развитие более надежных спутниковых архитектур, что в конечном итоге способствует повышению безопасности и эффективности космических миссий.

Ключевые слова: структурные отказы, механизмы отказа, материаловедение, мониторинг состояния, стратегии снижения рисков

Вклад авторов

Реза Каши Заде К. — введение, общий обзор, раздел 3, 5, 6, и заключение, написание текста; *Купреев С.А., Самусенко О.Е.* — анализ и научная проработка материалов, раздел 2, 3 и 4.

Финансирование

Статья подготовлена при поддержке Министерства науки и высшего образования Российской Федерации в рамках выполнения государственного задания по соглашению № 075-03-2024-059 (FSSF-2024-0005).

Заявление о доступности данных

Данные могут быть предоставлены по запросу.

Для цитирования

Reza Kashyzadeh K., Kupreev S.A., Samusenko O.E. Analytical review of the common failures of satellite structures: causes, effects, and mitigation strategies // Вестник Российского университета дружбы народов. Серия: Инженерные исследования. 2025. Т. 26. № 2. С. 127–134. http://doi.org/10.22363/2312-8143-2025-26-2-127-134

Introduction

The need for durable and reliable satellite structures has grown significantly with the rise of commercial space initiatives, Earth observation missions, and space exploration programs [1]. Satellites must be engineered to withstand a wide range of mechanical, thermal, and environmental stresses both during launch and in orbit [2]. Despite advancements, structural failures continue to be a major risk, often resulting in reduced functionality or mission loss. This study provides a comprehensive overview of common failure modes in satellite structures and examines their causes, effects, and mitigation strategies. This review synthesizes the findings from both industry and academia, focusing on failure mechanisms and design approaches that enhance the robustness of satellite structures.

1. Overview of Satellite Structural Components

Satellite structures include primary and secondary elements, each tailored for specific roles and designed to withstand unique stresses [3; 4]. The key structural components include the following:

Primary Frame (PF): This part provides the fundamental rigidity and load-bearing structure for the satellite [3].

Secondary Structures (SS): These support critical subsystems such as thermal control, propulsion, and payload interfaces.

Deployable Mechanisms (DM): This includes solar panels, antennas, and other extendable elements that activate post-launch.

Thermal Shielding and Insulation (TSI): Layers designed to manage extreme temperature changes.

Each of these components has distinct design requirements and associated failure risks owing to the environmental and operational factors. Figure 1 shows the satellite structural components with personal wireless communications [5].

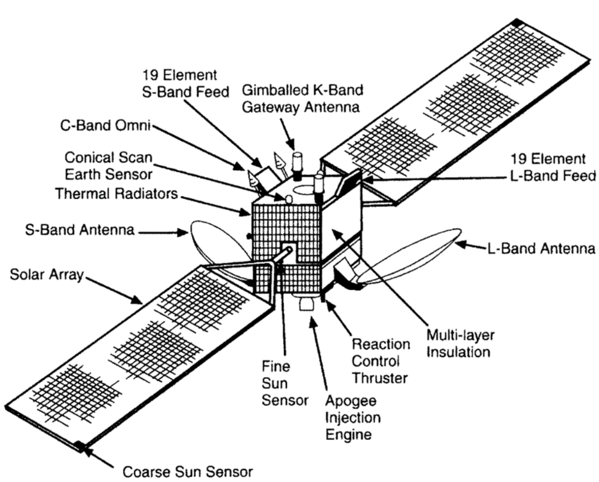

Figure 1. Diagram of satellite structural components
S o u r c e: made by R. Perez [5]

2. Common Causes of Structural Failures in Satellites

2.1. Vibrational and Acoustic Loads During Launch

The launch phase subjects satellites to high levels of vibration and acoustic energy [6–8]. These forces often lead to structural fatigue and even catastrophic failure in sensitive areas such as joints and fasteners [9; 10]. Research has shown that vibrational frequencies experienced during launch can amplify stresses in weak points of the satellite structure, leading to fractures and detachment. Figure 2 demonstrates the vibration and acoustic testing of the JUPITER 3 satellite [11].

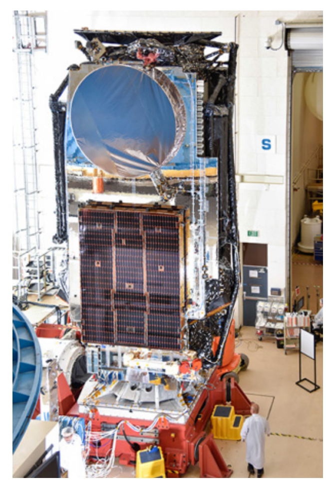

Figure 2. The vibration and acoustic testing on the JUPITER 3 satellite
S o u r c e: by Hughes. Available from: https://www.hughes.com/resources/insights/inside-hughes/theres-whole-lot-shakin-going-jupiter-3-undergoes-vibration-and (accessed: 18.03.2025)

2.2. Thermal Stresses Due to Orbital Environment

Satellites are exposed to extreme thermal cycling between the sunlit and shaded sides of the Earth, causing materials to expand and contract repeatedly [11; 12]. Thermal cycling can degrade composite materials, lead to adhesive breakdown, and create microcracks in metals and polymers [13], particularly in Low Earth Orbit (LEO) [14; 15]. A schematic of the thermal exchange between a space-craft and the space environment is provided below [16], (Figure 3).

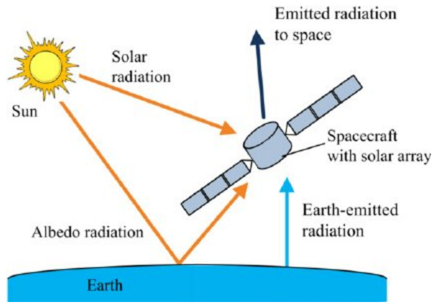

Figure 3. Thermal exchange between spacecraft (solar array) and space environment
Source: by J. Li, S. Yan, R. Cai [16]

2.3. Radiation-Induced Degradation

Radiation from solar and cosmic sources causes material degradation, leading to embrittlement and reduced structural integrity over time [17; 18]. Studies on polymer degradation and metal embrittlement indicate that radiation exposure significantly shortens the lifespan of structural materials used in satellite construction [19; 20].

2.4. Micrometeoroid and Orbital Debris Impacts

Micrometeoroids and space debris represent constant hazards in orbit, especially in LEO [21; 22]. Even small impacts can lead to pitting and localized structural damage, compromising shielding and initiating fatigue. Figure 4 shows the front and rear sides of the impact feature on a solar array [23]. In this figure, the diameter of the opening on both sides is approximately 5 mm, whereas the central hole has a diameter of 0.5 mm.

2.5. Manufacturing and Assembly Anomalies

Manufacturing inconsistencies and assembly errors contribute to structural vulnerabilities. Defects in welding, material inconsistency, and improper alignment can manifest as significant structural issues during the operational lifetime of satellites [24; 25].

3. Types of Structural Failures in Satellite Components

3.1. Frame and Panel Failures

The frame and panels form the primary load-bearing structure of a satellite. Failure modes include:

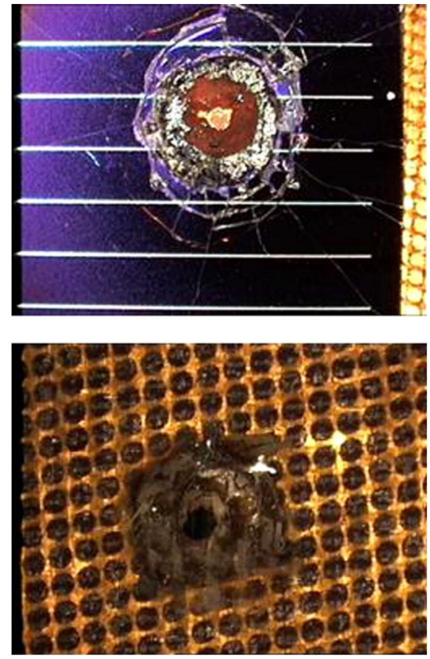

Figure 4. Front and rear sides of impact feature on HST solar array
Source: by G. Drolshagen [23]

◆ *Buckling and Cracking:* Occurring under high mechanical loads, especially during launch [26; 27].

◆ *Corrosion:* In LEO, exposure to atomic oxygen causes the surface degradation of metal and polymer-based components [28–30].

3.2. Joint and Fastener Failures

Joints and fasteners play a crucial role in maintaining structural integrity [31]. Common failures include the following:

◆ *Thermal expansion discrepancies:* Caused by different expansion rates in dissimilar materials, which can weaken the joints over time.

◆ *Cold welding:* In a vacuum environment, metals can bond unintentionally, leading to potential joint failures.

3.3. Deployable Mechanism Failures

Deployable structures such as solar arrays and antennas face unique challenges:

◆ *Stuck deployments:* Due to binding from debris or thermal distortions.

◆ *Spring and hinge fatigue:* Resulting from thermal cycling leading to impaired deployment capabilities.

3.4. Thermal Shielding and Insulation Failures

Thermal management systems are crucial for satellite operation. Failure modes include:

◆ *Insulation degradation:* Particularly for multi-layer insulation exposed to prolonged radiation [32; 33].

◆ *Micro-Cracking:* In thermal layers due to extreme expansion and contraction.

4. Case Studies of Structural Failures in Satellite Missions

4.1. ISS Solar Array Deployment Anomaly

The 2007 tear in the ISS solar array was attributed to fatigue in the deployment mechanism [34]. This case highlighted the importance of material durability in deployable structures and led to the integration of stronger and more resilient materials in later designs.

4.2. Envisat Gyroscope Mount Failure

The Envisat mission experienced a gyroscope mount failure, largely due to an under-designed mounting bracket. This case demonstrated the need for robust mounting mechanisms for sensitive instrumentation.

4.3. Orbcomm-1 Series Vibration Damage

The Orbcomm-1 satellites suffered structural damage owing to insufficient vibrational damping during launch. Since then, enhancements in damping mechanisms have been implemented to mitigate similar risks.

5. Mitigation Strategies and Emerging Technologies

5.1. Advanced Materials and Coatings

In this particular application, research into advanced composites and coatings aims to increase resistance to radiation and thermal cycling:

◆ *Carbon Fiber Composites (CFC):* This type of composite is used for primary structures owing to its strength-to-weight ratio [35].

◆ *Radiation-Resistant Polymers (RRP):* They are used to prevent embrittlement and maintain material integrity over extended missions [36–38].

5.2. Enhanced Testing and Simulation Techniques

It is imperative that vibrational and thermal testing be conducted under realistic conditions:

◆ *Accelerated Thermal Cycling Tests (ATCT):* It simulates orbital conditions to predict long-term material performance [39].

◆ *Finite Element Analysis (FEA):* It helps anticipate the points of failure under various load scenarios [40–44].

5.3. Real-Time Structural Health Monitoring

Incorporating sensors and diagnostic tools allows for real-time monitoring:

◆ *Embedded strain gauges:* These are generally used to detect stress points and initiate predictive maintenance.

◆ *Sensor-Based predictive maintenance:* Data-driven models use health monitoring to proactively schedule maintenance or adjustments [45; 46].

5.4. Reinforcement of Joints And Fasteners

Material selection and thermal compatibility improvements enhance joint performance:

◆ *Thermally compatible alloys:* It prevents cold welding and differential expansion in joints.

◆ *Improved fastener designs:* These were developed to resist both vibrational and thermal cycling stresses.

6. Future Directions in Satellite Structural Design

Emerging research in adaptive structures and self-healing materials shows promise for reducing the impact of micrometeorite damage and thermal stress. Additionally, AI-driven simulations and autonomous health-monitoring systems are expected to play a pivotal role in satellite design, enabling smarter and more resilient structures for long-term missions.

Conclusion

This study critically examined the common structural failures in satellite systems, focusing on their causes, effects, and mitigation strategies.

The research employed a comprehensive review of historical and recent satellite failures, integrating case studies, experimental findings, and advancements in materials science and structural health monitoring.

Through this analysis, we systematically investigated the key structural failure modes, including vibrational stresses during launch, thermal cycling effects in orbit, radiation-induced degradation, and micrometeoroid impacts. The study further evaluated failure-prone components, such as primary frames, joints, thermal shielding, and deployable mechanisms.

The findings highlight several advancements that can enhance satellite resilience. Notably, the adoption of carbon fiber composites, radiation-resistant polymers, and thermally compatible alloys has shown promise in mitigating structural degradation. Additionally, enhanced testing techniques, real-time structural health monitoring, and improved fastener designs have contributed to reducing failure risks.

By synthesizing current knowledge and emerging technologies, this study provides valuable insights for the development of more robust satellite structures. The proposed advancements aim to enhance the reliability and longevity of space missions and ensure improved performance under extreme environmental conditions.

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