

Review

Advances in Composite Materials for Space Applications: A Comprehensive Literature Review

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Abstract: Space structures are perhaps the most complicated man-made structures due to their extremely harsh and complex operational environments. For these structures, materials serve as crucial technology drivers. Composite materials are increasingly used in space structures due to their specific mechanical properties, customizability, and ability to easily acquire multifunctional and smart characteristics. This review critically examines the state of the art in composite materials application and the computational models used to design and analyze composite space structures.

Keywords: composites; space structures; computational models; sustainability

1. Introduction

A comprehensive space research program encompasses activities in the sectors of Earth observation, satellites, connectivity, and space exploration. In all these sectors, but especially in satellites and space exploration, challenging structures are involved where materials serve as technology drivers. Space structures need to operate under severe dynamic thermomechanical loads, endure an intense chemical environment, and simultaneously possess advanced electromagnetic properties. Space materials technology is mainly driven by developments in the aviation sector. Consequently, in the past decade, there has been a transition from monolithic materials to composite materials in space applications.

Despite the high scientific interest and the increasing number of reported works, only a few papers have been published aimed at summarizing the literature on the use of composite materials in space applications. These reviews mainly focus on spacecraft, without generalizing to other space structures of major importance. The review by May et al. [1] includes only non-polymer composite materials, while the review by Ince et al. [2] focuses on emerging composite materials. Tiwary et al. [3] provided a brief overview of the advances of space-grade materials, including metallic alloys, for the construction of the space shuttle. A review published in a NASA-held conference [4] highlighted the available manufacturing methods of composites, while Narayana and Burela [5] and Sairajan et al. [6] focused only on the available works for multifunctional composite materials. Moreover, there is no published review on the computational models used for the design and analysis of composite space structures. In the present paper, the state of the art and prospects of composite applications and computational models are critically reviewed. In addition to the structural aspects, the sustainability of space structures is also addressed. This comprehensive review aims to identify the progress of research in the subject of space-grade composites, categorizing the existing literature with regard to the adverse phenomena expected to be encountered in the inhospitable space environment and the material type.



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2. Boundary and Loading Conditions of Space Structures and Applications

The mission of spacecraft and satellites can be divided into three main phases: ground operations, flight operations, and space operations, while the mission of satellites includes only the first two phases. At each mission phase, different loads and environmental conditions apply for space structures. Ground operations are the least demanding phase for structures and materials. Flight operations include launch and flight in Earth's atmosphere. Space operations for spacecraft include flight in outer space, landing on another planet, and exploration works. The boundary conditions for the ground, flight, and space operation phases are shown in Figure 1.

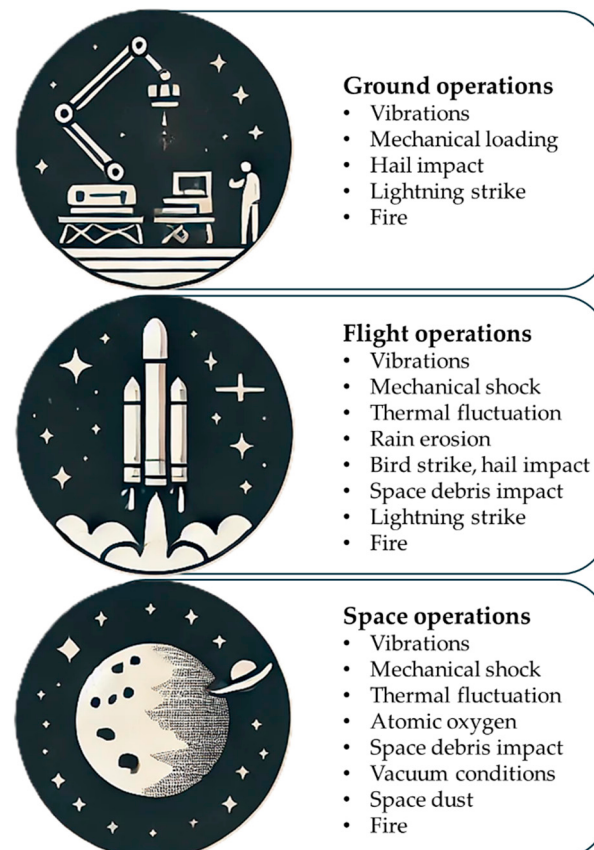


Figure 1. Boundary and loading conditions of space structures.

Hence, optimizing composite materials for space applications is crucial due to the extreme environmental conditions they must endure. Material properties in urgent need of optimization include the following:

- **Radiation Resistance:** Spacecraft and satellites are exposed to high levels of cosmic radiation and solar particle events. Materials need improved resistance to degradation from gamma rays, X-rays, and energetic particles.
- **Thermal Stability:** Extreme temperature fluctuations in space require materials with high thermal resistance, low thermal expansion, and stability under thermal cycling.
- **Strength:** Structural materials need to be both lightweight and extremely strong to optimize payload efficiency, especially for launch vehicles and deep-space missions.
- **Durability Against Atomic Oxygen Erosion:** Low Earth orbit environments expose materials to highly reactive atomic oxygen, which erodes polymers and some metals.
- **Low Outgassing:** Materials must have minimal volatile emissions in vacuum conditions to prevent contamination of sensitive instruments and optics.

- **Self-Healing and Repairable Surfaces:** Self-repairing materials could help mitigate micro-meteoroid and debris damage in space, improving the longevity of spacecraft structures.
- **Cryogenic Toughness:** Materials used in cryogenic fuel tanks and components must maintain mechanical integrity at extremely low temperatures.
- **Electromagnetic Shielding:** Advanced materials are needed to protect electronics from space weather effects, including electromagnetic interference and radiation-induced failures.
- **Improved Adhesion and Coatings:** Space coatings need better adhesion and wear resistance for thermal control, radiation shielding, and reducing contamination.
- **3D Printability and In Situ Manufacturing Adaptability:** Materials must be optimized for additive manufacturing in space, enabling in-orbit repairs and construction.

3. Types of Space Composites

Various types of composite materials have been studied for space applications, utilizing useful properties of either the matrix or the reinforcement. Table 1 presents the different types of composites across different space applications and loading conditions.

Table 1. Listing of types of composites for different space applications and loading conditions.

Material	Application	Loading
CFRPs	Damping [7]	
	Outgassing and contamination [8]	
	Coatings [9]	
	Load-bearing structure [10]	Vibration [20]
	Grid structures [11]	Dynamic loading [21]
	Deployable structures [12,13]	Mechanical–thermal [22]
	Hydrogen permeability [14]	Aging/Degradation [23–25]
	Radiation shielding [15]	Hypervelocity impact [26]
	Radiator [16]	Erosion [27]
	Outgassing effect [17]	
Kevlar/epoxy	Damping [7] Outgassing effect [17]	Thermoelastic [28]
Metal matrix composites	Melting, solidification [29]	Radiation [30]
Aramide/polyimide	Friction and wear [31]	Tribological testing
Carbon/polyimide		
Carbon/carbon-(Zr-Si-B-C-O)	Extreme temperature [32]	
GFRPs	Self-lubrication [33]	Outgassing effect [17]
	Geodetic beams [34]	
	Deployable structures [12]	
	EMI shielding [35]	
Nanofilled CFRPs	Radiation shielding [36–38]	Thermal–electrical [19,39,40] Electron irradiation [41]
Bio-based CFRPs	Space applications	Mechanical [42]
Carbon/SiC	Coatings	Mechanical [43]
Hybrid CFRPs	Spacecraft fuselages	Mechanical [42,44]

Table 1. Cont.

Material	Application	Loading
TiB ₂ /TiC/Ni	Space shielding systems Front shield bumpers	Hypervelocity impact [38,45–47]
Zylon/epoxy		
Twaron/epoxy		
Nanofilled GFRPs		
Aramid/epoxy		
Silver/epoxy (3D printed)	Thermal conductivity [48]	
Iron/PEEK (3D printed)	Magnetic properties [49]	
Ceramic matrix composites	Space applications [50,51] Oxidation resistance [52]	Mechanical Thermal
Multifunctional CFRPs	Fracture toughness [53]	Thermal shock Nano-indentation Mechanical Vibration
	Deployable structures [54]	
	Self-healing [55]	
	Structural health monitoring [56]	
	Micro-strain and temperature sensing [57]	
	Shape memory [58–60]	
Ti/polymer	Shape memory [61]	Thermal cycling

4. Mechanical Response

Mechanical loads of space structures are divided into static loads caused by gravity and dynamic loads (fatigue, high strain rate, vibration, impact, etc.). Most of the published works have focused on dynamic loads.

4.1. Vibration and Damping

Only a few papers have studied the vibration and damping of composite space structures (Table 2). Marchetti et al. [7] studied experimentally the damping characteristics of CFRPs, GFRPs, and kevlar/epoxy composites on the basis of beams and plates, while O’Neil and Hollaway [20] studied experimentally the vibrational characteristics of space composite structures in conjunction with analytical and numerical models. Their combined work enabled the assessment of the local and global modal behavior of skeletal systems. More recently, Cao et al. [62] studied the coupled vibrational characteristics of a spacecraft composed of a flexible composite shaft and solar panels, where the latter are fixed on the shaft. They proposed a power series multiplier polynomial method aimed at the establishment of connecting and matching conditions between the components. Both analytical and numerical validation of the employed method was presented on a simplified basis (1D shaft, 2D panels); hence, its applicability to a more representative model must be studied. In [63], Baier presented the design aspects of composite aerospace structure under vibrational loads. Serving as a more holistic approach on the subject, this book chapter incorporates various case studies ranging from passive/active dampening to more space-oriented problems such as vibro-acoustic excitation during the launch phase of space rockets due to propulsion systems, aerodynamic turbulence, etc. The author concluded that the approach of the vibrational design of composite structures is not that far from that of monolithic materials, providing extra tailoring capabilities via the beneficial use of anisotropy.

Table 2. Listing of articles about vibration and damping.

Author	Subject	Method	Notable Results
Marchetti et al. [7]	Structural damping of composites	Experimental and numerical	Dissipation energy estimation and correlation
O'Neill and Hollaway [20]	Dynamic characteristics of skeletal configurations	Experimental and numerical	Allocation of the supports enhances modal behavior
Cao et al. [62]	Connecting conditions of shaft/solar panel	Analytical	Higher-order frequency relative error less than 4%

4.2. Mechanical Properties/Behavior

Studies on the mechanical performance and properties of space composites focus on either characterizing conventional composites under space conditions or developing advanced hybrid composites with improved attributes (Table 3).

One of the earliest studies on space composites, conducted by [34], analyzed the mechanical and physical properties of hybrid unidirectional graphite–glass thermoplastics (HMS/E-glass/P1700) used in geodetic beams. This work is merely incorporated in this review to demonstrate the early research interest for composite materials in space applications, along with the early realization of their high application potential due to low thermal distortion along with high stiffness. Similarly, the thermomechanical behavior of kevlar/epoxy composites was experimentally assessed in [28], where the study's results indicated a higher thermal expansion of kevlar-reinforced polymers than CFRPs. Experimental evaluation of a composite shell structure's load-bearing capacity under varying loads was performed in [10]. Testing the annular wound IMS-65 E23 24K + Huntsman composite shells yielded results regarding the influence of combined force loads (tension, compression, and internal pressure) among design and technological factors. Meanwhile, [22] examined the thermomechanical properties of polyaryl–ether–ketone reinforced with functionalized carbon microfibers (F-CF) before and after electron beam irradiation. The insertion of F-CF by melt mixing resulted in a 6% increase in tensile strength prior to the 500 kGy dose, while a decrease in elongation to failure was observed for all the specimens that underwent irradiation. Innovations addressing specific challenges in space composites have also been documented. For instance, [44] introduced a novel thermosetting–thermoplastic polyimide composite aerogel to tackle the poor energy absorption and irreversible deformation issues of aerogel materials used in spacecraft fuselages. The experimental evaluation of the developed substance presented improved compressive strength (0.85 MPa) and compressive modulus (3.93 MPa), along with thermal insulating properties and good resistance to fatigue. The impact of rubber particles on the mechanical properties of polymer composites was experimentally investigated in [42]. Specifically, nitrite and natural rubber particles were embedded into carbon-fiber-reinforced epoxy followed by tensile and flexural mechanical evaluation. It was found that the flexural properties were enhanced via the integration of the two particle types, while the tensile properties were degraded for the nitrite-enriched specimens. Delkowski et al. [53] developed a plasma-enhanced cross-linked poly(p-xylylene) diamond-like carbon superlattice material for enhanced mechanical integration with soft polymeric and composite materials. This technology enables the coupling of hard–soft layer materials, providing enhanced elastic modulus and higher temperature, crack, and shear resistance than the classical poly(p-xylylene) deposition for space-grade structures. Surface treatment and processing of thermoplastic composites, specifically carbon fibers/polyphenylene sulfide (CF/PPS), for aerospace applications were explored in [9], where the authors achieved seamless integration of a silicon nitride surface layer. On a broader scale, Giusto et al. [11] proposed three applications for composite grid

structures in payloads and launch vehicles, detailing the preliminary design approach and material selection process. Efforts to reinforce composites using nanoparticles were reported in [36,39], with [39] achieving a 500–625% enhancement in the thermal and electrical conductivities of CFRPs through the addition of carbon nanotubes, enabling effective electroplating of the material.

Table 3. Listing of articles about mechanical properties/behavior.

Author	Subject	Method	Notable Results
Garibotti et al. [34]	Development of composite geodetic beam	Experimental	Weight can be minimized via varying beams' diameters
Crema et al. [28]	Evaluation of mechanical/thermal properties	Experimental	Greater thermal expansion of kevlar fabric than CFRP
Kravchuk et al. [10]	Annular wound shell evaluation under combined loading	Experimental	Thermal expansion is less stable in circular direction
Peter et al. [22]	Thermomechanical evaluation of F-CF-reinforced PAEK after irradiation	Experimental	Irradiation slightly decreased the ultimate strain of the material
Sun et al. [44]	Introduction of new thermoplastic–thermosetting polyimide aerogel	Experimental/manufacturing	High compressive strength (0.85 MPa), high compressive modulus (3.93 MPa)
Jeremy J. Samuel et al. [42]	Evaluation of rubber particles dispersion into the composite	Experimental	Natural rubber increased both tensile and flexural strength
Delkowski et al. [53]	Development of plasma-enhanced poly(p-xylylene) superlattice material	Experimental/manufacturing	The structures presented higher elastic modulus, improved temperature, and shear resistance compared to the classically deposited poly(p-xylylene)
De O.C. Cintra et al. [9]	Surface treatment of CF/PPS via plasma-enhanced chemical vapor deposition	Experimental/manufacturing	The silicon nitride layer was measured at 275 ± 53 nm
Giusto et al. [11]	Preliminary design of three composite space-oriented substructures	Manufacturing/design	Automated dry parallel filament winding and resin infusion were proven most efficient
Vartak et al. [39]	Electrical conductivity enhancement of CFRP via MWCNTs	Experimental/manufacturing	Addition of 0.4% MCNTs enhances the conductivity to meet space-grade requirements
Seibers et al. [36]	Enhancement of mechanical properties of HDPE for radiation shielding	Experimental/manufacturing	Introduction of alkylated reduced graphene oxide enhanced the tensile modulus by 10–15%
Lv et al. [31]	Investigation of wear and friction behavior of carbon and aramid fibers	Experimental	CF/polyimide composite presented high wear resistance even in irradiated environments
Colas et al. [33]	Self-lubrication performance evaluation of four composite types	Experimental	PTFE/(10% MoS ₂ , 25% glass fibers) composition presented the best tribological properties

Finally, the friction and wear properties of composites were studied experimentally in [31,33]. Research in [31] tested carbon/polyimide (CF/PI) and aramid/polyimide composites under simulated space irradiation where the enriched materials demonstrated a superior wear resistance due to the decrease in the friction coefficient. A start–stop friction process was also utilized resulting in the aggravation of the polymer wear rate, while the CF/PI composite maintained relatively stable behavior, with the latter standing as a potential tribological material for space applications. Colas et al. [33] evaluated four self-lubricating composite configurations designed for ball bearing lubrication. The polymeric matrix was PTFE with varying compositions of MoS₂ particles, glass, and mineral fibers.

The tribological test held both in UHV and air environments suggested that the PTFE/(10% MoS₂, 25% glass fibers) composition was the most prominent candidate for the replacement of current self-lubricating composite systems, providing good transfer capability and stable friction.

4.3. Hypervelocity Impact

Hypervelocity impacts caused by space debris or micro-meteoroids present a high risk for space structures. However, the published work is limited (Table 4). There have been two works reported on the design of novel shields and bumpers, one work on the impact toughness of CFRPs and one work on novel testing methods. In [45], a novel shield configuration with a front bumper made from a TiB₂-based composite was designed and tested. A series of tests at 3 km/s, 5 km/s, and 7 km/s velocities were conducted on both the composite Whipple-type shield and its aluminum counterpart. The debris cloud generated behind the composite bumper consisted of smaller fragments in comparison to the metallic shield, resulting in reduced impact damage at the rear structure. In [26], the efficiency of directly curable carbon, Zylon, and Twaron composites as front bumpers for inflatable space structures was evaluated experimentally. The testing configuration consisted of the various bumpers followed by two aluminum witness plates, where the damage of a spherical projectile was assessed. The superiority of the composite bumpers was evident via the experimental procedure for a 3.3 km/s hypervelocity impact. In [46], the effect of density, type of weaving, width of fibers, and the number of layers of fiberglass and basalt fabric on impact toughness were studied. Also, CNTs were introduced into a polymeric matrix to enhance impact toughness. In [47], a hypervelocity impact shielding system for space stealth applications, incorporating electromagnetic wave absorption capability, was developed and validated from the design phase to the fabrication phase. The structure presented excellent microwave absorption at −10 dB from 6.65 GHz to 18 GHz, while impact behavior at 2.7 km/s–3.2 km/s was comparable to that of the aramid/epoxy composite. An alternative approach was proposed in [21] where the authors presented a characterization of the behavior of a CFRP under dynamic loading in the frame of its application as a thin shield for satellite protection. A wide strain rate domain was evaluated via planar plate tests, electron beam shocks, and laser-induced shocks, providing valuable insight into the characterization of composites as primary or secondary shields in space structures.

Table 4. Listing of articles about hypervelocity impact.

Author	Subject	Method	Notable Results
Huang et al. [45]	Impact performance evaluation of TiB ₂ -based composite shield configuration	Experimental	Smaller debris clouds were produced than aluminum bumpers
Kim et al. [47]	Examination of Zylon and Twaron composites as front bumpers under high-velocity impact	Experimental	An increase in velocity led to superior results for composites
Kobzev et al. [46]	Parametric study of composites' impact toughness	Experimental	Randomly dispersed CNTs enhanced impact toughness by 2.5–3%
Nam et al. [47]	Proposition of a shielding system with improved microwave absorption performance	Experimental/manufacturing	The structure presented superior impact performance to pristine aramid/epoxy at 2.7–3.2 km/s velocities
Jaulin et al. [21]	Performance of planar plate impacts and laser shocks at CFRP	Experimental/numerical	The simulation developed was validated for the performed tests

5. Thermal Response

In a very early work [64], research on the minimization of the effects of curing cycles, kinds of materials, layup typology, and mold configuration on the residual thermal stresses and distortions of composite antenna reflectors on space platforms was conducted. The developed methods were able to predict the residual distortions as functions of manufacturing parameters. In [65], a high-temperature thermal protection system made from ceramic matrix composites with active cooling, achieved by gas flow into the sandwich's core, was investigated. The heat exchange of the protection system under Earth re-entry conditions was evaluated by means of 3D thermal-fluid dynamics analysis. In order to improve the thermomechanical heat storage performance of silica gel/CaCl₂ composites and to evaluate their multi-cycle stability, a new synthesis protocol based on successive impregnation/drying steps by using a matrix with a broad pore size distribution was proposed in [66]. In [22], the thermal properties (melting and degradation temperature) of PAEK reinforced with functionalized carbon micro fibers was studied before and after electron beam irradiation, and an improvement was found. In [67], the high-temperature space charge dynamics of epoxy composites containing micro- and nano-AlN fillers under a high electric field were investigated. It was found that the addition of fillers significantly improves the thermal conductivity of the epoxy resin. In [16], testing and modeling of the spaceflight-quality of a high turndown ratio morphing radiator prototype in a relevant thermal environment are reported. In [19], a highly conductive CFRP electronic housing was manufactured. Aiming to reduce total energy costs in manufacturing, an out-of-autoclave manufacturing process was followed. Pitch-based carbon fibers were used to increase the thermal conductivity of the composite material. The results indicate potential gains of around 23% in mass reduction when compared to conventional aluminum electronic boxes. Hyde [50] highlighted the potential of ceramic matrix composites for space applications due to their exceptional thermomechanical properties, findings that were later supported by research in [43,64]. The latter works propose that ceramic/glass matrix composites stand as a high-potential materials for space applications, combining high strength and stiffness, dimensional stability, intrinsic damage tolerance, and creep and thermal shock resistance. The articles found regarding the subject of composites' thermal response are summarized in Table 5.

Table 5. Listing of articles about thermal response.

Author	Subject	Method	Notable Results
Ferrari et al. [65]	Investigation of the thermal protection performance and heat dissipation of a porous ceramic core	Numerical/ manufacturing/ experimental	A low-weight, additively manufactured component was designed with the desired properties
Dai et al. [67]	Investigation of high-temperature space charge dynamics of composites under high electric field	Experimental	Introduction of micro-nano particles increased the thermal conductivity of the matrix
Martins et al. [19]	Thermal conductance investigation of CFRP electronic boxes	Manufacturing/ experimental	The pitch-based CFRP achieved high thermal conductivity with 23% mass reduction compared to aluminum counterparts
Hyde [50]	Mechanical/thermal evaluation of ceramic composites	Experimental/ manufacturing	Applicability for extreme temperature applications
Zhang et al. [43]	Mechanical evaluation under simulated space environment	Experimental	30 MPa strength fluctuation after 100 thermal cycles
Marchetti et al. [64]	Minimization of manufacturing and thermal distortion	Analytical	[0 ± 60] _s layup showed better behavior than cross-ply laminates

6. Electrical, Electromagnetic, and Radiation Shielding

6.1. Electrical Conductivity

Similarly to the mechanical properties, the reported works on the electrical properties of space composites can be categorized into those that have characterized conventional composite materials under space conditions and those that propose new hybrid composites with enhanced properties.

A representative work on hybrid composites is the work of [40], in which the authors studied the electrical properties of CNT epoxy composites containing low CNT loadings (less than 1%). The measurements were conducted in situ, while the specimens were exposed to diverse simulated space conditions. The experimental results showed a reduction in resistivity by 40% due to the simultaneous exposure to high temperatures and low pressures, while the application of simulated sunlight with the concomitant surge in temperature showed a maximum decrease of 58%.

6.2. Radiation and Shielding

In [37], an experimental and analytical study on the radiation-protective characteristics of multilayer polyimide/lead composites subjected to X-ray radiation was performed. Meanwhile, the authors in [41] studied the resistance to electron irradiation of polyimide composite with nano-sized lead filler. The experimentally measured X-ray attenuation coefficients for 10–88 keV energies suggested that the proposed PI/nanodispersed Pb composite provides considerable gains for radiation protection. In [15], energetic ion beam experiments with space radiation elements, ^1H , ^4He , ^{16}O , ^{28}Si , and ^{56}Fe , were conducted to investigate the radiation shielding properties of composite materials. These materials are expected to be used for parts and fixtures of space vehicles. In [38], a shield that absorbs microwave irradiation was developed for incorporation into an ultra-high-molecular-weight polyethylene (UHMWPE)/hydrogen-rich benzoxazine (HRB) composite for cosmic radiation shielding and to prevent electronic malfunction. Grafting of multi-walled carbon nanotubes (MWCNTs) on polydopamine (PDA)-coated fibers was attempted to control permittivity. The composite can achieve a radiation dose reduction of 16.2% compared to currently employed technologies, along with a 22.9% weight reduction. In [52], fully dense ZrB_2 and HfB_2 composites were elaborated by Spark Plasma Sintering (SPS) with 20 vol% TaSi_2 to replace SiC aiming to improve their oxidation resistance. Introduction of TaSi_2 provided oxidation resistivity up to 2170 K, which is beyond the upper limit of its counterpart, although it is not an ideal replacement for high-velocity atmospheric re-entry applications. In [35], the potential of manufacturing high-concentration Graphene Nano-Platelet (GNP) films using liquid thermoplastic Elium[®] resin was explored. The manufactured composites exhibited excellent EMI shielding effectiveness and showed increases in impact energy absorption, strength, and stiffness by 105%, 48%, and 45%, respectively, compared to pristine GFRPs. In [30], the mitigating space radiation using magnesium(-lithium) and boron carbide composites was studied. It was found that the lower atomic mass of these materials increased nuclear fragmentation upon cosmic radiation interactions, leading to a softening of the secondary (neutron) radiation spectra. Table 6 lists all the relevant literature found on the radiation and shielding properties of composite materials.

Table 6. Listing of articles about radiation and shielding.

Author	Subject	Method	Notable Results
Cherkashina et al. [37]	Radiation protection assessment by multilayer polyimide structure containing lead nanoparticles	Experimental	X-ray attenuation coefficients for the structure were 12–15% higher than the predicted values
Naito et al. [15]	Study on the radiation protection of CF/PEEK	Experimental	The composite materials presented >30% higher shielding efficiency than aluminum
Cha et al. [38]	Cosmic radiation shielding via HRB/UHMWPE composite	Design/ experimental	Apart from excellent electromagnetic absorption, interlaminar shear strength was achieved
Pellegrini et al. [52]	Replacement of SiC with fully dense ZrB ₂ and HfB ₂ for high-temperature oxidation resistance	Manufacturing/ experimental	The samples tested showed that the material is not suitable for re-entry applications
Khan et al. [35]	Investigation of EMI performance and impact resistance of GNP films with glass-fiber-reinforced Elium [®] composites	Manufacturing/ experimental	High EMI shielding effectiveness and superior impact behavior, strength and stiffness compared to pristine GNP/GFRP
O'Connor et al. [30]	Radiation dose reduction by replacing aluminum with boron carbide composites	Analytical	Dose reduction was measured at 5% for small areal densities and 10–15% for larger areas (>50 g·cm ²)

7. Environmental Degradation and Aging

In a pioneering work, Startsev and Nikishin [23] experimentally studied the aging of hybrid polymer composites by exposing them to real outer space conditions for 1501 days through employment on a spacecraft (Table 7). They measured the strain and strength parameters as well as the mass, density, and thickness changes in the composite materials and found that the principal, dominant process occurring due to the continuous presence in outer space was the post-curing of the resin materials, which in turn affected the mechanical characteristics of the composite materials. In the same year, Paillous and Pailler [24] simulated the long-term exposure of composite laminates in space by subjecting them to electron radiation combined with thermal cycling, or to oxygen atom fluxes. The results show that the synergistic action of electrons and thermal cycling degrades the matrix by chain scission, crosslinking, and microcrack damage, altering the composite's properties. In [27], high-dose implantation at energies in the 10–100 keV range using ions of metal or semiconductor materials was used to modify the surface of polymeric materials to produce changes that could yield improvements in space environmental durability. The results show that computer modeling of the ion implantation process combined with reasonable fluence estimates provides a good basis for the choice of implantation conditions. The implantation of silicon and aluminum (singly, binary, or in combination with boron) or yttrium produces a stable, protective oxide-based layer following exposure to HAO. The improvement in chemical resistance of these materials ensures performance without deterioration in long-duration space missions. In a recent work, He et al. [25] studied the effects of atomic oxygen on three commercial composite materials, based on two space-qualified epoxy resins (tetraglycidyl-4,40-diaminodiphenylmethane (TGDDM) cured with a blend of 4,40-methylenebis(2,6-diethylaniline) and 4,40-methylenebis(2-isopropyl-6-methylaniline); and a blend of TGDDM, bisphenol A diglycidyl ether (DGEBA), and epoxidised novolak resin initiated by N'-(3,4-dichlorophenyl)-N,N-dimethylurea). Samples were exposed to a total

fluence of $(3.82 \times 10^{20} \text{ atom/cm}^2)$, equivalent to a period of 43 days in low Earth orbit. The flexural rigidity and modulus of all laminates displayed a reduction of 5–10% after the first exposure (equivalent to 20 days in orbit).

Table 7. Listing of articles about degradation and aging.

Author	Subject	Method	Notable Results
Startsev and Nikishin [23]	Investigation of aging in space environment for hybrid epoxy-based composite	Experimental	The room-temperature composite strength was not degraded after 1501 days in space
Paillous and Pailler [24]	Simulation of space environment for graphite/epoxy laminates by electron radiation/thermal cycling	Experimental	Significant microcracking was observed causing residual strains and thermal expansion alterations
Iskanderova et al. [27]	Surface modification by high-dose ion implantation at 10–100 keV for environmental durability enhancement	Analytical/numerical/experimental	The modified specimens showed no morphology alteration after exposure to HAO
He et al. [25]	Evaluation of the simulated atomic oxygen effect, equivalent to 43 days in low orbit, on three composites	Experimental	The exposure resulted in surface erosion, leading to decreased flexural properties

8. Advanced Composites

8.1. Shape Memory Composites

In [61], theoretical calculations and experimental studies were carried out to predict the maximum value of reversible deformation of a composite material based on a polymer matrix reinforced with titanium nickelide fibers (Table 8). The experimental procedure revealed that up to 10% reversible deformation can be achieved for the examined composite due to thermal cycling, which makes the development of transformable space structures feasible. In [58], an experimental study was conducted on a shape memory polymer composite to be used in space antenna reflectors. The studies showed that the composite material has the required shape memory effect and is promising for producing frames only with thermal insulation. In [59], shape memory polymer actuators based on carbon resistive heating fibers and epoxy matrix were developed for space applications. Their mechanical, thermal, and electrical properties, as well as their deployment kinetics under both ambient and vacuum conditions, were studied. In [60], for the first time, shape memory polymer composites (SMPCs) were exposed to a low Earth orbit environment by the MISSE-FF platform: two carbon-fiber-reinforced laminates with an SMP interlayer were retrieved after 1 year of exposure, and tested on Earth. Results show that flight samples behaved differently, because of their different orientation on MISSE-FF. The applied deformed shape was partially recovered on the sample with zenith orientation during its exposure, but neither flight sample showed any additional shape recovery on Earth. The other sample, with wake orientation, froze the non-equilibrium shape permanently.

Table 8. Listing of articles about shape composites.

Author	Subject	Method	Notable Results
Kollerov et al. [61]	Estimation of the reversible deformation of titanium nickelide fibers' reinforced composite	Analytical/ experimental	Maximum reversible deformation during thermal cycling can be achieved by selecting the optimal ratio of the rigidity of the matrix and reinforcing fibers
Moskvichev et al. [58]	Definition of the optimal parameters for preserving reversible behavior for space antenna composite	Experimental	Since temperature severely influences mechanical properties, it should be controlled to ensure proper deploying behavior
Margoy et al. [59]	Mechanical, thermal, electrical, and deployment dynamics assessment of carbon heating resistive fiber composite	Experimental	The aluminum-coated composite achieved 24% lower electrical power consumption and faster deployment

8.2. Self-Healing Composites

A review paper has been published on self-healing composites for space applications [68]. However, most of the works that have been reviewed do not relate to space applications. On the other hand, only a few papers have been published in this category. The most representative is the work of [69]. This study explored the application of self-healing composites on impacted space structures. The developed material consisted of microcapsules containing blends of 5-ethylidene-2-norbornene (5E2N) and dicyclopentadiene (DCPD) monomers, combined with ruthenium Grubbs' catalyst. These materials were integrated into an epoxy resin matrix, further enhanced with single-walled carbon nanotubes (SWNTs) through a vacuum centrifuging technique. The resulting nanocomposites were infused into woven carbon-fiber-reinforced polymers (CFRPs). The CFRP specimens were subjected to hypervelocity impact conditions, mimicking the harsh environments encountered in space, using a hypervelocity launcher. This study assessed the self-healing capabilities under these conditions, with particular emphasis on the contribution of SWNTs. The nanotubes played a pivotal role in enhancing the mechanical properties and facilitating the healing process. As discussed with respect to the experimental parameters, the single-wall nanotubes assisted the composite's self-repair process by acting as cross-links in the released 5E2N polymer after its polymerization with the Grubbs catalyst. This research represents a significant step toward the development of materials capable of autonomously repairing damage in space environments, ensuring the structural integrity and longevity of space components.

8.3. Smart/Sensorized Composites

In [56], a smart CFRP structure with embedded piezoelectric lead zirconate titanate transducers was used to detect multiple areas of artificial delamination and real impact damage using nonlinear ultrasound. The experimental results revealed that the proposed configuration of embedded piezoelectric lead zirconate titanate transducers (PZTs) can be utilized for on-board ultrasonic inspection of spacecraft composite parts. In [57], percolation-based sensors were introduced into Graphite–PDMS (poly di-methyl siloxane) composites for measuring micro-strains and temperature. Changes in both temperature and strain can be sensed by measuring the change in resistance across the electrodes of the sensing element. In [66], a new synthesis protocol was proposed to improve the performance of composite materials based on a silica gel loaded with CaCl_2 . This new protocol allows the production of composite materials with high salt content and high stability, which are required for sea-

sonal thermochemical heat storage applications, outperforming previously reported results. Table 9 summarizes the three available articles dealing with smart/sensorized composites.

Table 9. Listing of articles about smart/sensorized composites.

Author	Subject	Method	Notable Results
Andreades et al. [56]	Real-time composite damage detection via PZTs with nonlinear ultrasound	Experimental	Multiple damage locations of different sizes in composites were successfully detected
Oppili Prasad et al. [57]	Optimization of highly stretchable strain sensors using CNT/PDMS composites	Manufacturing/experimental	A nearly linear strain sensitivity at the 0–5000 μ range was achieved
Courbon et al. [66]	Enhancement of the thermochemical heat storage of silica gel and CaCl_2 composites	Manufacturing/experimental	The method suggested yields to composite with high salt content (i.e., 43 wt% CaCl_2) and stability

9. Composites in Deployable Structures

Deployable structures are assemblies which do not aim for motion but rather to attain different configurations. They deploy from a folded state to a desired configuration. These structures are widely used in space applications due to storage limitations of launch vehicles. Therefore, they have been applied in structural designs and concepts for various aerospace missions, including space support booms, space deployable antennas, and solar panels, as well as flexible solar sails. In the last few years, research activities on composite deployable space structures have been intensified (Table 10).

In [54], a multifunctional composite hinge with integrated piezoelectric actuation capabilities for deployable space is developed. Finite element simulations and experimental testing are utilized to design and validate the multifunctional high-strain composite hinge. In [70], nonlinear dynamic modeling methods for a flower-like clustered deployable space telescope (DST) made of laminated composite material, experiencing large deployment and attitude adjustment motions, are presented. Moreover, experiments for evaluating the dynamic behavior of surrounding mirrors during simultaneous deployment using different deployment strategies were conducted. The numerical results are in good agreement with those obtained from experiments to validate the correctness of the present nonlinear modeling formulation. In [12], the geometrically nonlinear behavior of deployable composite booms undergoing large displacements and rotations was investigated. The mathematical model makes use of higher-order 1D structural theories based on the Carrera unified formulation, which allows the description of moderate nonlinearities and deep post-buckling mechanics in ultra-thin shells in a hierarchical and scalable manner. Particular attention is given to studying the equilibrium paths of booms subjected to coiling bending. Dedicated experimental tests reveal the validity of the proposed finite element approach, whereas the investigation of different lamination sequences offers a valuable perspective for possible future designs. In [71], a practical FE-based design procedure for a new configuration of an anisogrid composite lattice spoke in an umbrella-type deployable reflector for a space antenna is presented. A parametric analysis was conducted, aiming to minimize the spoke's mass, incorporating the angle of orientation, the number and width of the helical ribs, and the width and height of the hoop ribs as design parameters. In a series of works [72,73], Liu and Bai studied the folding behavior of a deployable composite cabin (DCC) for space habitats using analytical methods [72] and numerical and experimental methods [73]. The analytical method proposed in the latter showed good correlation to the experimentally measured values, requiring only a few input parameters to achieve accuracy. In [13], a data-driven computational framework combining machine learning and

multi-objective optimization was developed for the design of space-deployable bistable composite structures with a C-cross section. A C-cross section thin-walled deployable composite structure exhibits bi-stability compared to other deployable structures, which has attracted much attention thanks to its application prospects in roll-out solar arrays. In order to obtain the optimal geometric parameters of subtended angle, thickness, initial radius, and longitudinal length, combination methods of the finite element method, the multi-objective optimization technique, and the experiment method for bistable composite structures with C-cross section are proposed in this article. In [74], the folding behavior of the tubular deployable composite boom was investigated by analytical modeling. Based on the Archimedes' helix, the geometrical model of the DCB was established. By combining the equilibrium equation and energy principle, an analytical model to predict the folding moment versus rotational displacement of the DCB was presented. The failure indices in the equal-sense and opposite-sense folding processes were calculated utilizing Tsai–Hill and maximum stress criteria. Analytical results agreed well with experimental and numerical results. Finally, the influence of geometric parameters (i.e., radius, central angle, and thickness of cross-section) on the folding behavior of the DCB was further studied using the analytical model.

Table 10. Listing of articles about composites in deployable structures.

Author	Subject	Method	Notable Results
Echter et al. [54]	Development of a multifunctional composite hinge for deployment of optomechanics equipment and post-deployment corrections	Numerical/ experimental	Accuracy for the deployment was achieved via feedback control using Macro Fiber Composite actuators
You et al. [70]	Simulation of clustered deployable space telescope	Numerical/ experimental	The FE model using shell elements in absolute coordinate formulation was validated experimentally at subcomponents
Pagani et al. [12]	Simulation of the geometrical nonlinear behavior of space booms using the Carrera Unified Formulation (CUF) for ultra-thin shells	Numerical	The used CUF method achieved accurate description of the near- and far-post buckling behavior of the structures
Morozov et al. [71]	Design of anisogrid composite deployable reflector based on parametric FE simulations	Numerical/ design	The helical angle had the most severe impact on the deformability, stress and buckling responses of the structure
Liu and Bai [72,73]	Folding behavior of deployable composite space cabin via experiments/simulation (Part I) and analytical approach (Part II)	Experimental/ numerical/ analytical	The proposed DCC consists of a composite circular roof and hollow thin-walled cylindrical composite structures
Zheng et al. [13]	Optimization of a C-cross section deployable composite structure geometric parameters	Numerical/ machine learning	The multi-objective optimization performed led to a space-grade structure according to NSGA-II
Liu et al. [74]	Investigation of the folding behavior of DCB and geometric parametric study	Analytical	Results show that the opposite-sense folding moment is greater than the equal-sense folding moment

10. Computational Models

Computational models have seen limited application in composite space structures compared to their widespread use in composite aerostructures. This disparity stems partly from the differences in constituent materials and, more significantly, from the unique loading and boundary conditions of space environments. Space structures are subject to complex phenomena, such as rain erosion, micro-meteoroid and space dust impacts, and atomic oxygen exposure, which are not yet fully described analytically or numerically. Existing computational efforts predominantly focus on the dynamic behavior of deployable structures [12,54,70–72,74]. For example, a data-driven methodology leveraging Long Short-Term Memory (LSTM) networks was proposed in [67] to detect multiple damage locations in solar arrays. These damage locations were generated using finite element models of the arrays. The deep learning framework's performance was assessed using two sensor types: accelerometers and piezoelectric patches. In both cases, the framework effectively identified damaged elements with limited time-series data. Additionally, [67] presented a numerical investigation into the thermomechanical performance and failure mechanisms of honeycomb core composite sandwich structures with bonded fittings under extreme temperature ranges. These studies highlight ongoing progress in adapting computational techniques to address the unique challenges of space-structure applications.

11. Conclusions

From the literature review of published journal papers on the space applications of composite materials, the following conclusions can be drawn:

- **Expanding Applications:** Composites are increasingly used in space structures, yet their application remains limited. There is a pressing need for new materials capable of withstanding combined loading conditions characteristic of the space environment.
- **Limited Publications:** The number of publications on this topic is relatively small compared to the wealth of information available online. This limitation is partly due to much of the research being conducted within national or cooperative space programs, which often restricts public dissemination.
- **Material Challenges:** The harsh space environment demands advanced mechanical, thermal, and electrical properties. Research is ongoing into novel matrix and fiber materials, hybrid composites, lattice reinforcements, and nanoparticle enhancements. Although significant improvements in properties have been achieved, current composites remain brittle and weak under cryogenic conditions and are prone to degradation at high temperatures. These challenges are particularly pronounced for large-volume applications. Thus, further work is required for the optimization of composite structures in the space environment.
- **Role of Computational Models and AI:** Computational models have primarily been applied to deployable structures. Combined with artificial intelligence, they hold great potential for advancing the simulation-driven design of next-generation composite materials.
- **Rapid Developments:** Deployable structures, structural health monitoring (SHM) concepts, and smart composites are advancing rapidly, offering promising avenues for the future of composite space applications.

This review underscores the importance of continued material innovation and computational advancements to meet the stringent demands of space environments.

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