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# Space engineering — Structural materials handbook

Part 1: Overview and material properties and applications

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# Space engineering - Structural materials handbook - Part 1: Overview and material properties and applications

Ingénierie spatiale - Manuel des matériaux structuraux - Partie 1: Vue d'ensemble, propriétés des matériaux et applications

Raumfahrttechnik - Handbuch der Konstruktionswerkstoffe - Teil 1: Übersicht und Materialeigenschaften und Anwendungen

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# European Foreword

This document (CEN/TR 17603-32-01:2022) has been prepared by Technical Committee CEN/CLC/JTC 5 “Space”, the secretariat of which is held by DIN.

It is highlighted that this technical report does not contain any requirement but only collection of data or descriptions and guidelines about how to organize and perform the work in support of EN 16603-32.

This Technical report (CEN/TR 17603-32-01:2022) originates from ECSS-E-HB-32-20 Part 1A.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN [and/or CENELEC] shall not be held responsible for identifying any or all such patent rights.

This document has been prepared under a mandate given to CEN by the European Commission and the European Free Trade Association.

This document has been developed to cover specifically space systems and has therefore precedence over any TR covering the same scope but with a wider domain of applicability (e.g.: aerospace).



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# Introduction

The Structural materials handbook is published in 8 Parts.

A glossary of terms, definitions and abbreviated terms for these handbooks is contained in Part 8.

The parts are as follows:

| | | | |
|---|---|---|---|
| TR 17603-32-01 | Part 1 | Overview and material properties and applications | Clauses 1 - 9 |
| TR 17603-32-02 | Part 2 | Design calculation methods and general design aspects | Clauses 10 - 22 |
| TR 17603-32-03 | Part 3 | Load transfer and design of joints and design of structures | Clauses 23 - 32 |
| TR 17603-32-04 | Part 4 | Integrity control, verification guidelines and manufacturing | Clauses 33 - 45 |
| TR 17603-32-05 | Part 5 | New advanced materials, advanced metallic materials, general design aspects and load transfer and design of joints | Clauses 46 - 63 |
| TR 17603-32-06 | Part 6 | Fracture and material modelling, case studies and design and integrity control and inspection | Clauses 64 - 81 |
| TR 17603-32-07 | Part 7 | Thermal and environmental integrity, manufacturing aspects, in-orbit and health monitoring, soft materials, hybrid materials and nanotechnoligies | Clauses 82 - 107 |
| TR 17603-32-08 | Part 8 | Glossary | |



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# 1 Overview

## 1.1 Scope

### 1.1.1 General

The structural materials handbook, SMH, combines materials and design information on established polymer matrix composites with provisional information on the emerging groups of newer advanced materials and their composites. Design aspects are described, along with factors associated with joining and manufacturing. Where possible, these are illustrated by examples or case studies.

### 1.1.2 Polymer composites

The polymer composite materials described are those having continuous fibre reinforcement in a polymer matrix, i.e.:

- Continuous fibre reinforcement, [See: [2-3]
  - Carbon
  - Aramid
  - Glass
- Thermosetting polymer matrix, [See:[2-4]]:
  - Epoxy, [See:2.4,3.2].
  - Polyimide, [See:6.12].
  - Bismaleimide, [See:6.6].
- Thermoplastic polymer matrix, e.g. PEEK, PEI, PES, [See: 6.17].

### 1.1.3 Advanced materials

Information on the characteristics and applications is given for:

- Magnesium alloys and their composites, [See: Clause 44].
- Aluminium alloys and their composites, [See: Clause 46].
- Titanium alloys and their composites, [See: Clause 47].
- Superalloys and their composites, [See: Clause 48].
- Intermetallic materials, [See: Clause 49].



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- Refractory metals, [See: Clause 50].
- Beryllium, [See: Clause 51].
- Technical ceramics, [See: Clause 43]
- Ceramic matrix composites, [See: Clause 52].
- Glass and glass-ceramic matrix composites, [See: Clause 53].
- Carbon-carbon composites, [See: Clause 54].

Data on conventional structural materials is not included in detail. Reference is made to the appropriate documents for aerospace applications.

# 1.2 Polymer-based composites

## 1.2.1 Background

### 1.2.1.1 Development

The advent of high-performance reinforcing fibres in combination with thermosetting polymers was heralded in the 1960's as the arrival of a new group of materials to compete with and, in many cases, replace conventional metals. In retrospect the claims made at that time were somewhat premature, but subsequent development has produced a wide range of materials with useful properties.

The early materials offered were under constant revision by their manufacturers using both the results of their own research and that of other organisations. This was aimed at optimising fibres, polymer resin formulations and manufacturing methods, all of which contribute to the material characteristics. An effect of this constant development was that data on polymer composite materials became redundant rapidly, because the materials themselves changed specification during the research programme. As a result, designers and users, encouraged by the results of initial studies, found it difficult to apply polymer composites.

The main contributing problems in this were:

- Availability of a consistent source of a material.
- Lack of proven characteristics under the whole range of operational or service conditions.
- Lack of design data, since the flexibility of composites enabled materials to be created with highly directional properties. This was a significant departure from traditional metal behaviour and needed the development of methods for measuring properties and correction factors for different environmental degradation mechanisms.
- Poor understanding of the fracture and failure characteristics. Composites differ from metals and fracture mechanics methods are not easily translated to composites with anywhere near the same reliability.
- Scarcity of design tools that enabled the designers to achieve the same level of safety confidence as for metals, given the fact that the design approach needed for composites was significantly different from that for metals.
- New means of testing and verification of materials, components and structures. Those applied to metals needed modification or development. New procedures were also necessary.



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- New means of inspecting and correlating findings to structural performance. Again, those techniques applied to metals had to be modified and proven. The types of defects or inconsistencies in composites are completely different in both appearance and effect from those found in metals.

Until these demands were fulfilled, the opportunities for composite materials were severely limited. At about this time, the initial claims made for composites replacing metals were revised and it became accepted that composites complement rather than replace metals in structural applications.

#### 1.2.1.2 Aerospace and defence

As with the development of most 'new materials', their initial applications were foreseen within the aerospace and defence sectors. Here high-value components and structures could tolerate the higher cost of the materials themselves, provided that the perceived performance and weight-saving benefits were realised. The strategic importance of composites was recognised, and considerable budgets were assigned world-wide to develop the necessary technical understanding.

Table 1.2-1 compares composites with conventional materials, Ref.[1-1]. It demonstrates the basis for the interest in their use in high strength, high stiffness to weight applications or where dimensional stability is a crucial demand.

**Table 1.2-1 - Comparison of specific strength and stiffness for composite materials and conventional aerospace structural materials**

| | **Specific strength** ($\times 10^3$ N/kg/m) | **Specific stiffness** ($\times 10^6$ N/kg/m) | **Density** ($g/cm^3$) |
|---|---|---|---|
| Unidirectional carbon/epoxy: | | | |
| HS - high strength | 1850 | 100 | 1.5 |
| IM - intermediate modulus | 1450 | 115 | 1.6 |
| HM - high modulus | 550 | 200 | 1.7 |
| Aramid/epoxy | 1200 | 50 | 1.4 |
| Glass/epoxy | 980 | 25 | 1.8 |
| Aluminium | 180 | 25 | 2.8 |
| Titanium | 240 | 25 | 4.4 |

Table 1.2-2 shows the potential of composites over aluminium in a developed aircraft structure, Ref. [1-1]. Although the costs of the composite replacements were considerably higher than the metal counterparts, in time and with experience of rationalised design and manufacturing processes, the cost-benefit relationships have become more attractive.



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**Table 1.2-2 - Comparison of early composite and aluminium aircraft structures**

| L-1011 Aileron Structure | Aluminium | Composite |
|---|---|---|
| Weight (kg) | 63.9 | 47.2 |
| Weight-saving | - | 26% |
| Number of ribs | 18 | 10 |
| Part count | 398 | 205 |
| Number of fasteners | 5253 | 2574 |

Figure 1.2-1 shows the chronological progress in the use of composite materials for military applications, Ref. [1-1].

Some examples of the use of composites in military aircraft, as a percentage of overall structural weight, include:

- F/A-18E 'Hornet' composite content 18%.
- Lockheed F/A-22 composite content 20%.
- AV-Harrier II composite content 26%.
- F-35 Joint Strike Fighter composite content 35%.

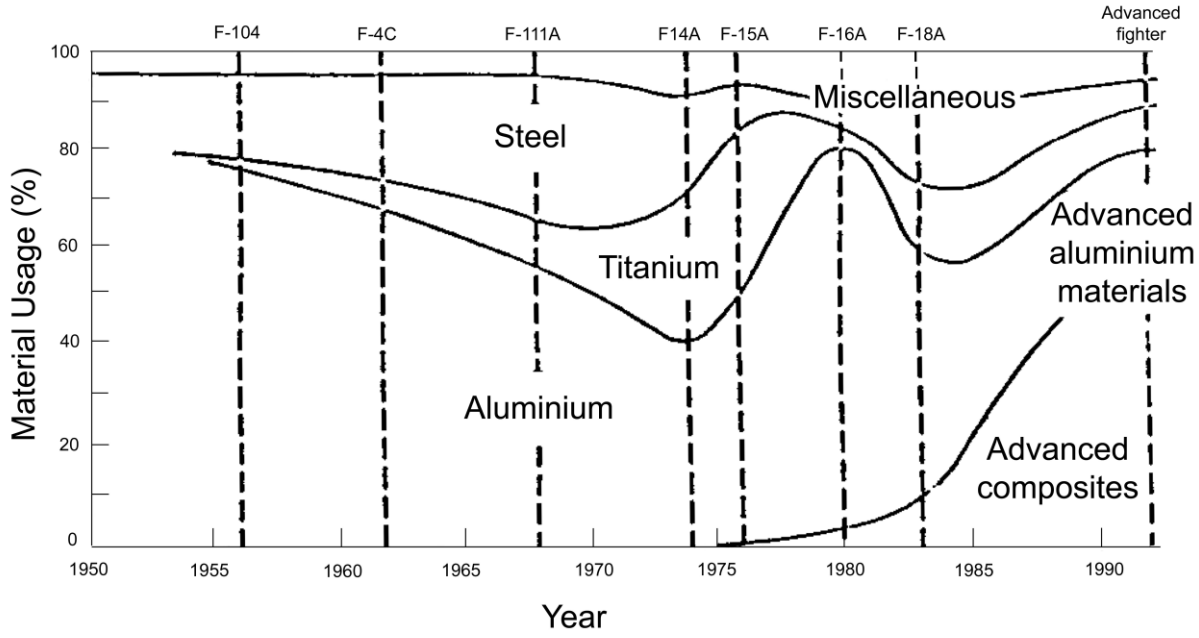



**Figure 1.2-1 - Chronological progress of the application of composite materials in military applications**



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### 1.2.1.3 Civil aircraft

Application of composites within civil aircraft lagged behind military use owing to:

- Cost.
- Safety; more critical both to manufacturers and certification agencies.
- General conservatism resulting from past experiences of financial penalties from equipment down-time.
- Availability of experience of military flight and service.

Increasing confidence in composite materials, largely from numerous military-based applications, along with extensive work concerned with the development and proving of suitable design and testing approaches, eventually aided their acceptance within civil aircraft. This was, by necessity, a gradual and cautious process.

The aircraft industry sought to use more composites instead of metal to create more fuel-efficient aircraft. In recent commercial aircraft, composites now account for about 10% to 25% of the total weight. Some examples of applications are small fuselage components, tails and selected parts of wings, e.g. trailing-edge flaps.

Within the Airbus-series, in 1985 the tail fin of the A310 was made of composite. About 22% of the A380 is composite, Composite wings are envisaged for the A350.

At the end of 2005, Boeing announced, that 50% of the structural weight of its 787 aircraft is intended to be made of composite, including the fuselage.

### 1.2.1.4 Space industry

Until the volume use of new materials increased in other unrelated industries, with the benefits of reduction in price and increased knowledge, their use in the smaller volume industries, such as space, was not feasible.

Whilst the value of space-destined structures is high, the volume usage of materials in the space industry is remarkably low. Some of the technical demands are similar to military or civil aircraft, whereas others are very specific to the operational environment of space. The majority of materials used in space structures come from those developed for other industries, but proven to behave in a reliable, predictable manner under the very specific service conditions of space. The basic principles and policies applied to material and process selection are summarised in Table 1.2-3 and Figure 1.2-2, Ref. [1-2].

**Table 1.2-3 - Material usage in European space projects**

| Materials for Space Applications | | |
|---|---|---|
| Practice: | ~90% | Plain commercial materials |
| | ± 9% | Advanced materials developed in other technological areas, e.g. aeronautics, automobiles. |
| Rationale: | | Space application is small, with a high quality demand. |
| Consequence: | | Great effort to be made towards:<br>1. Establishing suitable test methods to ensure that commercial materials operate satisfactorily in orbit.<br>2. Screening commercial materials by applying these test methods. |



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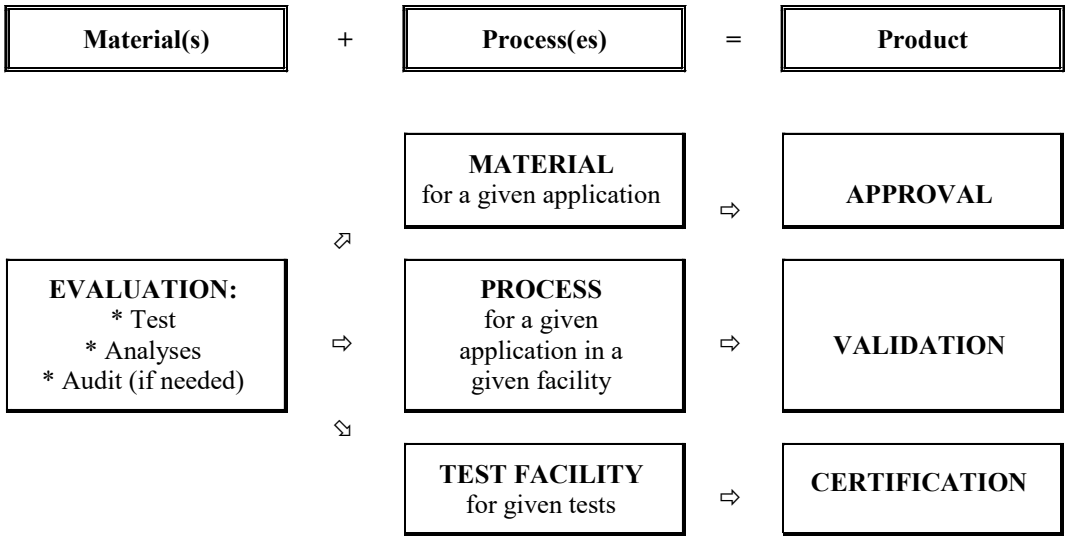



**Figure 1.2-2 - Acceptance process for materials, processes and test facilities**

For example; In launcher structures that use materials with a proven track-record in other industries, helps not only with material selection, but also for aspects of design, manufacturing processes, and inspection.

Together with the growing experience of military use, composite materials became of greater interest to the space industry as demands increased for mass-efficiency. Thus reducing the cost of launch and deployment, in the increasing number of military, civilian satellites and research payloads. During this period the emphasis placed on 'new technology at any price' shifted to 'new technology at the right price'. This new approach also served to concentrate the minds of the material manufacturers, who consolidated their product ranges and increased the reliability and supply of materials to increase product confidence.

Figure 1.2-3 provides an illustration of the evolution of structural materials within some European space projects, Ref. [1-5].



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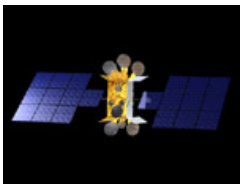
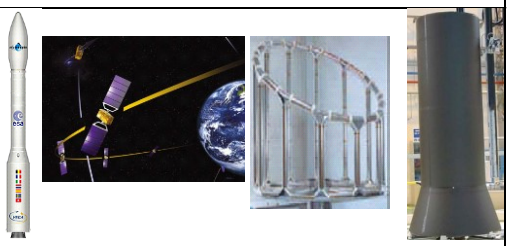
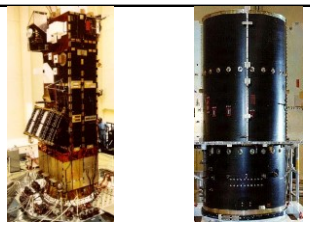
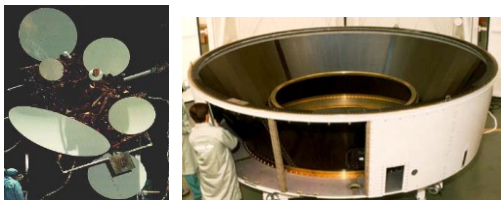
| | | |
|---|---|---|
| 2005 > | Materials: Composite materials re-convergence with civil aircraft (demand for CFRP). Automation of CFRP gridded structures. Emergence of specially-designed 'molecular materials' + nanotechnologies; Multifunctional structures.<br>AlphaBus (large satcom platform). |  |
| 2000 > | Composite materials applied to new large projects: Galileo (navigation-positioning); Vega launcher. Monolithic and gridded designs compete with some sandwich structures. New welding processes for metal-based pressurised structures.<br>New material developments: 'Inflatable structures' + optical structures, e.g. SiC ceramics. |  |
| 1995> | 'Harmonisation' of material options; convergence of metals and composites used within aircraft.<br>Ariane 5 (ECA interstage): CFRP sandwich + monolithic CFRP (integrated composite rings) conical adapter; both made by fibre placement |  |
| 1990 > | Composite materials prevail (except for Hermes and Space Station); First 'smart structures'.<br>Artemis (central tube): Co-cured CFRP sandwich<br>Envisat (Polar Platform): Largest European satellite, to date. |  |
| 1985 > | Ariane 5: CFRP all uppers stages; VEB metal cylinder + CFRP sandwich inner cone<br>Hermes: Metals, MMC and CMCs<br>Columbus module (ISS): Metals, MMC an CMCs<br>Satellite primary structures, e.g. telecom: CFRP central tubes |  |
| 1980 > | First CFRP components and structures: antenna reflectors, solar arrays, optical benches, truss structures<br>Olympus satellite: CFRP sandwich panels (antennas)<br>Ariane 4: CFRP structures (VEB, fairing and payload adapters). |  |
| 1975 > | COS-B satellite: metal sandwich panels + stiffened shell (launcher interface)<br>Ariane 1: metal structures (tanks, stiffened shells-riveted stringers and frames; fairing; equipment bay; payload adapters) |  |

**Figure 1.2-3– Example of the evolution of structural materials in some European space projects**



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## 1.2.2 European space industry perspective

### 1.2.2.1 Approach

Within European aerospace companies, the number of individual organisations working on all aspects of fibre-reinforced composites was, and remains, considerable. ESA was the first to recognise that, where several organisations contributed to a project, there was a need to consolidate the efforts. It is considered that much more can be learnt and progress made effectively if the information developed by one organisation is available to other project members, and eventually to related future programmes. In seeking to improve the performance of aerospace structures, the harmonisation and standardisation of information and design data are crucial. With budgets under more severe scrutiny by the contributing nations, the ability to progress in a more cost-effective manner was an obvious advantage, if it is shown not to interfere with the policies of individual, contributing organisations.

### 1.2.2.2 Information

With the need for appropriate information identified, work began in 1984 to bring together and disseminate technical information, developed mainly within Europe, on fibre-reinforced polymer composite materials for use on space projects. Under the control of ESA, this massive task was contracted to MBB/ERNO in Germany (which became Astrium and is now part of EADS) who acted as the organisers and recipients of information submitted by other organisations and also developed the framework and 1st edition of ESA PSS-03-1101: Composites Design Handbook; published in 1986. This contained a large amount of information, often unpublished elsewhere. Subsequently, the handbook evolved and enlarged considerably by periodic updating to include relevant innovations in design procedures, testing and analysis for the application of composites.

The methods needed to establish the properties and characteristics of polymer composites are reaching a level of understanding comparable with some conventional aerospace materials, but still have some way to go. One example is the need for standardised, proven methods for ensuring that their integrity is commensurate with that realised by conventional metals, and is maintained throughout their operational life. Composite materials remain under the ‘special requirements’ of the applicable fracture control documentation in recognition of the fact that linear elastic fracture mechanics technology is generally agreed to be inadequate. Therefore, fracture control currently relies on the techniques of containment, fail-safe assessment, proof and cyclic load testing, [See: ECSS-E-ST-32-01]. Until this subject is considered fully and it is proven that the safety requirements can be met, there remains a restriction on the use of composite materials and the possible mass-saving and performance increases achievable.

The structural materials handbook does not aim to impose a single ‘method’ for the use of composites. The aim is to provide information and guidance on their application within the framework of materials for space projects; hence the ECSS ‘informative’ designation.

[See also: Introduction – Source materials; Introduction – Background]



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# 1.3 Metal and ceramic-based composites

## 1.3.1 Background

The European objectives have grown to include manned, re-usable launch vehicles and long-term deployed, possibly manned, space structures. Very high safety and reliability factors for manned vehicles are additional to those of single-shot launchers and their payloads. Certain parts of these structures are on the performance limit of fibre-reinforced polymer composites and possibly also that of the conventional metals used.

## 1.3.2 Materials technology

Largely as a result of re-usable structures projects, a further round of materials research, development and proving began with the NASA Space Shuttle, and particularly its external TPS thermal protection system. Research continues today as new projects call for new materials advances and the prospective designs and specifications develop. These new composite materials, also described as 'advanced materials', are no longer based on polymers whose high temperature capabilities are limited, but are either metallic- or ceramic-based.

Figure 1.3-1 summarises the temperature requirements for some future space structures and materials with potential for fulfilling the demands, Ref.[1-3]

The designer, again, is faced with a large number of potential materials, many of which claim to be sufficiently advanced in their development to be considered viable for current or future European space projects, [See also: Introduction – Source materials].

The materials and information presented within the structural materials handbook reflects the relative immaturity of the 'new generation' of composite materials. Validated data is only generated in large quantities by full-scale application of materials and from experience of working with them.

The handbook provides information and guidance on materials application within the framework of materials for space projects; hence the ECSS 'informative' designation.

Depending on the precise requirements, some applications can be fulfilled by several materials. Others, with more demanding temperature or environmental constraints, are limited to perhaps only one or two.



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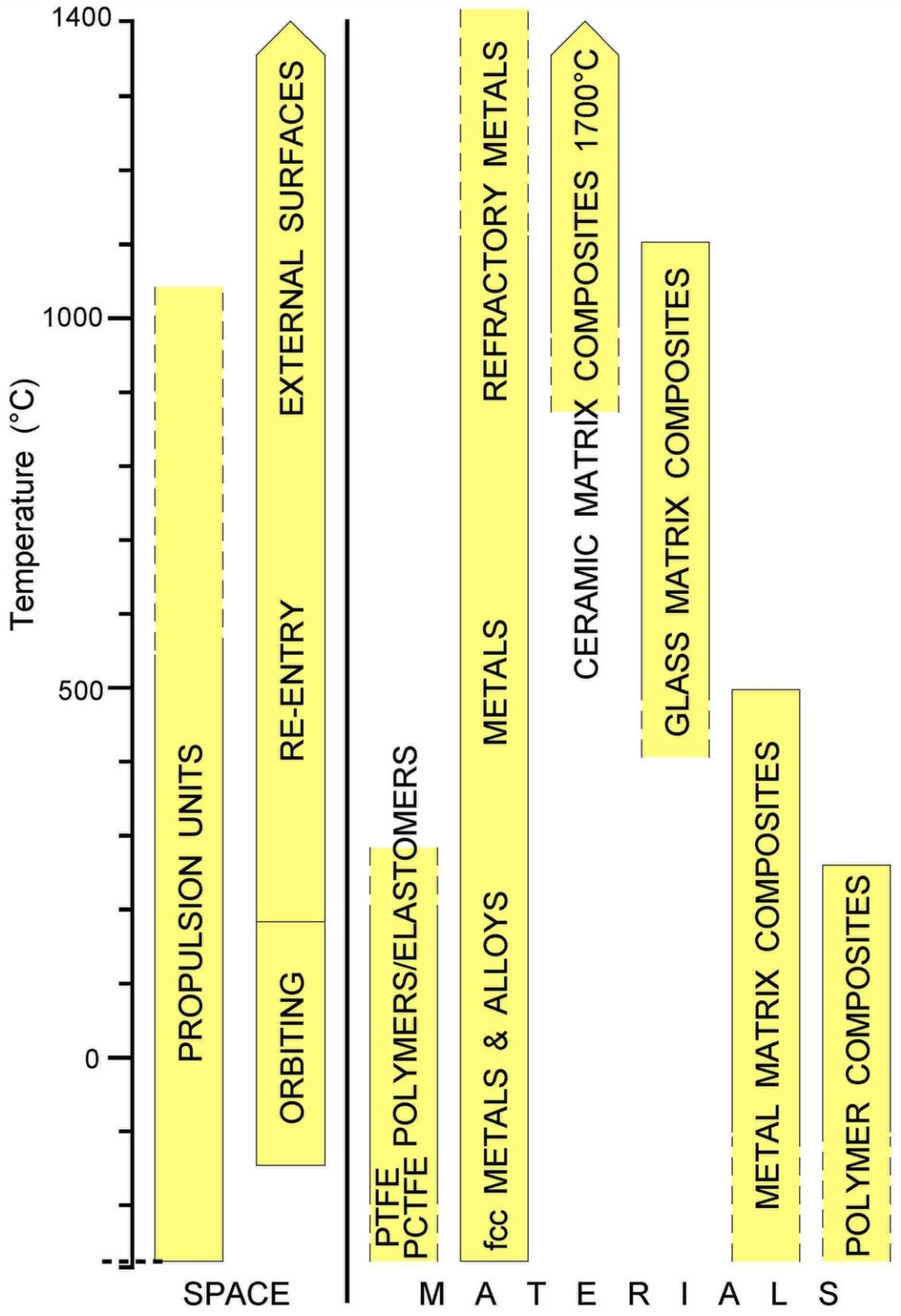



**Figure 1.3-1 - Temperature requirements for space structures and potential materials**



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In the development of metal and ceramic-based composites, some lessons learnt in designing with polymer composites are applicable, whereas others have to be reconsidered. The physical complexity of the newer materials has increased in an attempt to offset some of the recognised deficiencies of polymer-based materials. An example is the need to improve interlaminar characteristics by the use of fibres in three or more directions. This immediately raises the problem of establishing the properties of such a material. Coupon testing and its translation to structural properties are often no longer appropriate other than as a first comparison in the combined material and process development.

In addition, testing and inspection of these materials is often needed for complex geometrical shapes under realistic service conditions, either high temperature or long-term exposure in space. This significantly increases the difficulty, such that dedicated, realistic testing of items becomes the only feasible option. This led to the development of 'Centres of Expertise', in which material and component design, coupled with manufacture and testing, is conducted within one organisation. This is a significant departure from the metal and polymer composite industry, where materials were supplied from one or more sources to known or stated specifications. Components were then manufactured by various organisations, for later integration into the final structure.

Advanced materials also tend to increase the likelihood of single-source components, unless the technology is licensed to other parties. Development of expertise and facilities can be prohibitive on cost alone, hence the limited number of source organisations. Licensing is becoming more common as the associated technology moves from development into standard production processing, although this is not true for all materials. The trend has been set by some of the most technically developed ceramic-based materials, and others, yet to be fully optimised, are likely to follow.

Table 1.3-1 compares the development position of composite materials with traditional metals in aerospace applications. This indicates that whilst 'new' metals can be developed to expand the range of capabilities, the methods needed to establish their properties and characteristics already exist, backed up by many years of experience of other metals. Polymer composites are beginning to move towards this level of understanding, but still have some way to go, [See [1-2]. Considerable work remains to be done before the metal- and ceramic-based composites are at a stage of understanding similar to that of polymer composites. The number of possible applications for the newer advanced composites is limited to those where the other two groups cannot compete, owing to either the service conditions or the stipulated mass-performance.



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**Table 1.3-1 - Comparison of technology status for composite materials and traditional metals for aerospace applications**

| Design aspects | Traditional metals | Fibre-reinforced polymer composites | Advanced metal and ceramic-based composites |
|---|---|---|---|
| Material: | | | |
| Sources | Numerous | Several | Few |
| Specifications | Standardised | Established | Few |
| Basic advantages: | Well established. Known, proven performance history. Very wide range of standard materials available. | Proven mass/ performance benefits over some metal designs. Possibility to 'engineer' properties for the application. | Possible mass-to-performance benefits over some metal designs. Possibility to 'engineer' properties for the application. Structural uses at high temperatures and cryogenic. |
| Basic limitations | Structural uses limited to low/moderate temperatures, unless special grades applied. | Lower number of materials available. Structural uses limited to low/moderate temperatures. Dictated by the polymer matrix. | Limited number of proven materials available Many types still in development. No service experience. |
| Manufacturing: | | | |
| Methods | Well established | Established | Developing. |
| Specifications | Standardised | Established | Few |
| Sources | Numerous | Several | Few |
| Testing: | | | |
| Standard methods | Well established | Established | Developing |
| Test facilities | Numerous | Several | Few |
| Inspection | Well established | Established | Developing |
| Design tools | Well established | Available | Developing |
| Fracture control | Well established | Needs further development | Developing |
| Verification | Well established | Established | Developing |
| Usage and experience: | | | |
| Military | > 50 years | ~ 25 years | Limited |
| Aircraft | > 50 years | ~ 15 years | None |
| Space | Extensive | Moderate | Low (developing) |

As yet, a comparison on a cost-performance basis is difficult. There is a large body of information on metals, less for polymer composites and only limited data for the recent advanced material groups. Experience of polymer composites has shown that on material cost alone they cannot compete with conventional metals and there is no reason to assume that this is different for the new types of composites. Whilst the newer materials are currently very expensive, partly owing to the influence of low demand, the development of integrated material and component manufacture can provide cost benefits. For example, an integrally formed and joined structural panel reduces the number of manufacturing operations compared with standard sheet fabrication which is reflected in the overall



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item cost. Where production runs are small, the extent of this benefit is limited unless the cost of ownership also provides savings.

Table 1.3-2 summarises the technical benefits of the various broad groups within the family of advanced composite materials, Ref. [1-1]

**Table 1.3-2 - Comparison of technical aspects of various composite materials**

| | RELATIVE ADVANTAGE | | | | |
|---|---|---|---|---|---|
| **Material Properties** | Metals | Thermosetting Polymer Composites | Thermoplastic Polymer Composites | Metal Matrix Composites | Ceramic Matrix Composites |
| Corrosion resistance | X | XXX | XXX | X | XXX |
| Creep | X | XXX | XX | XX | XXX |
| Damage resistance | XXX | X | XX | XX | X |
| Design flexibility | XX | XXX | XXX | XXX | XXX |
| Fabrication: | XX | XX | XX | XX | XX |
| Time | X | XX | XX | X | X |
| Final part cost | XX | X | X | X | X |
| Moisture resistance | XXX | X | XX | XXX | XXX |
| Physical properties | XX | XX | XX | XX | XX |
| Processing cost | X | XX | XX | X | X |
| Raw material cost | XXX | XX | X | X | X |
| Reusable scrap | XXX | 0 | XX | 0 | 0 |
| Shelf life | XXX | X | XXX | XXX | XXX |
| Solvent resistance | XX | X | XX | XX | XX |
| Specific strength | X | XXX | XXX | XX | XX |
| Strength | X | XXX | XXX | XXX | XXX |
| Stiffness | X | XX | XX | XX | XX |
| Mass-saving | 0 | XX | XX | X | XX |
| **Space tolerance:** | | | | | |
| Out/off gassing | XXX | X | XX | XXX | XXX |
| Radiation | XXX | X | XX | XXX | XXX |
| Vacuum | XXX | X | XX | XXX | XXX |
| Dimensional Stability | X | XXX | XXX | XX | XXX |
| Thermal cycling | XXX | XX | XX | XX | XX |
| Limits for maximum service temperature | Alloy | Matrix type | Matrix type | Alloy matrix + fibre stability | Matrix + fibre stability |
| Key: XXX- Best; XX-Good; X-Fair; 0-Not Applicable | | | | | |

Within each main group, there are a number of materials possessing very different characteristics that can both compete with each other and with those in other categories. For example:

- Thermoplastic-based composites can be considered for applications currently fulfilled by thermosetting composites or by metals, such as conventional aluminium alloys.
- Metal matrix composites can compete with higher temperature capability thermosetting resin, thermoplastic composites or conventional metals.



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- Ceramic-based composites can be considered for higher temperature applications, possibly displacing Superalloys or other specially developed high temperature alloys with high densities.

In each case the new materials are disadvantaged by the lack of experience in their use.

Purely on a temperature comparison, the possibilities are many. However, other application factors usually reduce the options significantly. These include:

- Loads: Magnitude and direction of both static and dynamic loadings
- Dimensional stability
- Environment: On earth, during launch and in space, as summarised in Table 1.3-3

**Table 1.3-3 - Environmental factors for space structures**

| Environment | | |
|---|---|---|
| Earth | Launch | Space |
| Temperature | Vibration | Temperature |
| Moisture | Acceleration | Vacuum |
| Atmosphere | Shock | Radiation |
| Climate | Thermal flux | Debris |
| Biological | Lightning strike | Micrometeoroids |
| Physical | Bird strike | Atomic oxygen |
| | Rain erosion | Man activity |

# 1.4 Structural materials

## 1.4.1 General

The structural materials handbook, SMH, presents the design teams of European space projects with guidance and information on the application of many types of advanced composite materials; as summarised in Figure 1.4-1.

## 1.4.2 Materials

The term advanced composite materials describes:

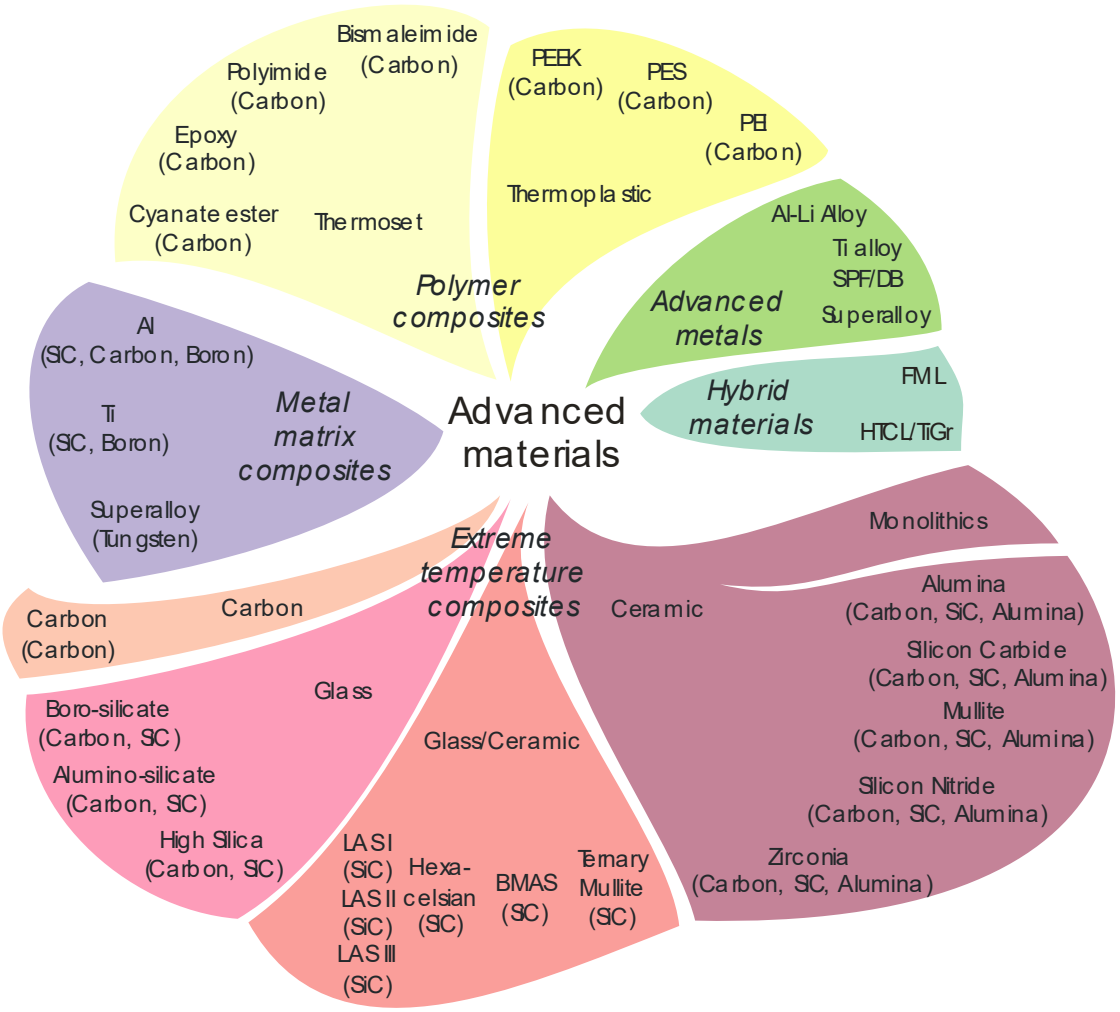
- Polymer matrix composites, where commonly used fibre-reinforced polymer composites, such as carbon/epoxy, have significant engineering data presented, along with information on glass or aramid fibres. Information is also given for the other polymer matrices, e.g. high-temperature resin systems, cyanate ester and thermoplastic-based materials.
- Advanced metals, such as aluminium-lithium, along with:
  - MMC 'metal matrix composites' with either continuous or discontinuous (particulate or whisker) reinforcements. As with polymer-based composites, continuous fibre-reinforced materials are viewed as more appropriate for structural applications.



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— Hybrid materials, which are combinations of continuous fibre-reinforcement, polymer matrix and metal, e.g. FML fibre metal laminates (aluminium); HTCL (titanium).

- Extreme temperature materials, originally developed for external surfaces of re-useable spaceplane concepts, but also finding applications within dimensionally-stable structures, e.g.:
  - — Ceramics, where some 'monolithic' technical ceramics are applied to structures whereas fibrous forms are for insulation.
  - — CMC: Ceramic matrix composites with either continuous or discontinuous reinforcements. Again, the continuous reinforced materials are likely to be used in structural applications.
  - — Glass- and glass-ceramics
  - — Carbon-carbon composites




Key: Matrix (Reinforcement)

**Figure 1.4-1 - Family tree of advanced materials**



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