MODERN COMPOSITES - A RENASCENT MATERIAL SYSTEM

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Abstract

Modern composites constitute an important class of design-and weight-efficient structural materials that are encroaching every sphere of engineering applications. Superior directional properties, high specific strength and stiffness properties, design tailoring, ease of manufacturing complex shapes as well as scores of other attributes make these materials ideally "Designers' Choice". The current material scenario is such that, unless a real breakthrough is made, these materials are destined to dominate through the twenty-first century. The present paper takes a cursory look into the early uses of composites and their impact on human civilisation as well as potential and growth of modern composites, namely, PMC, MMC and CMC in aerospace applications. A few numerical case studies are also presented to highlight the importance of CMC for high temperature applications.

Introduction

A composite is a material that is formed by combining two or more materials to achieve some superior properties. Almost all the materials which we see around us are composites. Some of them like wood, bones etc. are natural composites, as they are either grown in nature or developed by natural processes. The most remarkable features of woods and bones are that the low density, strong and stiff fibres are embedded in a low density matrix resulting in a strong, stiff and light weight composite. It is therefore, no wonder that early development of aeroplanes should make use of woods as one of the primary structural materials, and about two hundred million years ago, huge flying amphibians, Pterendons and Pterosaurs with wing spans of 8-15 meters, could soar from the mountains like present day hand-gliders. Woods and bones in many respects, may be considered to be predecessors to modern man-made composites. The main characteristics of woods and bones are that they are fibre reinforced composites having low weight and directional properties.

Early men used rocks, woods and bones effectively in their struggle for existence against natural and various kinds of other forces. The primitive people utilised these materials to make weapons, tools and many utility-articles and also to build shelters. In the early stages they mainly utilised these materials in their original form. They gradually learnt to use them in a more efficient way by cutting and shaping them to more useful forms. Later on they utilised several other materials such as vegetable fibres, shells, clays as well as horns, teeth, skins and sinews of animals. Woods, stones and clays, however, formed the primary structural materials for building shelters. Natural fibres like straws from grass plants and fibrous leaves were used as roofing materials. The limitations experienced in using these materials and search for better materials taught them later to combine two or more materials to obtain a more efficient material with better properties. This, in turn, laid the foundation for development of man-made modern composite materials.

The most striking example of an early man-made composite is the straw-reinforced clay which moulded the civilisation since prehistoric times. Egyptians, several hundred years B.C. earlier, were known to reinforce the clay-like deposits of the Nile Valley with grass plant fibres to make sun baked mud bricks that were used in making temple walls, tombs and houses. The watchtowers of the far Western Great Wall of China were supposed to have been built with straw-reinforced bricks during the Han Dynasty (about 200 years B.C.). The natural fibre reinforced clay, even today continues to be one of the primary housing materials in the rural sectors of many third world countries. The other classic examples are the laminated wood furniture used by early Egyptians (1500 B.C.), in which high quality wood veneers are bonded to the surfaces of cheaper woods. The origin of paper which made use of plant fibres can be traced back to China (108 A.D.). The bows used by the warriors under the Mongolian Chief Djingiz Chan (1200 A.D.) were believed to be made with the adhesive bonded laminates consisting of buffalo or antilope horns, wood, silk and ox-neck tendons.

The twentieth century has noticed the birth and proliferation of a whole gamut of new materials that have further consolidated the foundation of modern composites. Numerous synthetic resins, metallic alloys and ceramic matrices with superior physical, thermal and mechanical properties have been developed. Fibres of very small diameter (<10 mm) have been drawn from almost all materials. They are much stronger and stiffer than the same material in bulk form. The strength and stiffness properties have been found to increase dramatically, when whiskers (i.e. single crystal fibres) are grown from some of these materials. Because of the superior mechanical properties of fibres, the use of fibres as reinforcements started gaining momentum during the first part of the second half of the twentieth century. The aerospace industries took the lead in using fibre reinforced laminated plastics to replace several metallic parts. The fibres like glass, carbon, boron and kevlar and plastics such as phenolics, epoxies and polyesters caught the imagination of composite designers. One major advantage of using fibre reinforced plastics (FRP) instead of metals is that they invariably lead to a weight efficient design in view of their higher specific modulus and strength properties.

Composites, due to their heterogeneous composition, provide unlimited possibilities of deriving any characteristic material behaviour. This unique flexibility in design tailoring plus other attributes like ease of manufacturing, especially moulding to any shape with ploymer composites, repairability, corrosion resistance, durability, adaptability, cost effectiveness, etc. have attracted the attention of many users in several engineering and other disciplines. Every industry is now vying with each other to make the best use of composites. One can now notice the application of composites in many disciplines starting from sports goods to space vehicles. This world-wide interest during the last three decades has led to all round advancement in the field of composite materials and structures. Several high performance polymers have now been developed. Substantial progress has been made in the development of stronger and stiffer fibres, metals and ceramic matrix composites, manufacturing and machining process, quality control and nondestructive evaluation techniques, test methods as well as design and analysis methodolgy. The modern man-made composites have now firmly established as the future material and are destined to dominate the material scenario right through the twentyfirst century.

Aerospace Engineering

One of the primary requirements of aerospace structural materials is that they should have low density and, at the same time, should be very stiff and strong. Early biplanes used wood for structural frameworks and fabrics for wing surfaces. The fuselage of World War I famous biplane fighter named Vieux Charles was built with wire braced wood framework. The monoplane, Le Monocoque, had an unusually smooth aerodynamic design and its fuselage was made with laminated tulip wood. Almost all biplanes and monoplanes with a very few exceptions, were built of wood during the first quarter of the twentieth century. Lighter woods like balsa, poplar, spruce, tulip, etc. were more popular. Soaring planes, in those days, also had highly polished thin plywood fuselages.

The 'thirties' and 'forties' noticed a gradual shift from wood to aluminium alloy construction. With the increase in the size and speed of airplanes, the strength and stiffness requirements for a given weight could not be met from wooden construction. The trend continued till "fifties, by which almost all types of airplanes were of all-metal design.

However, the limitations of aluminium alloys could be assessed as early as fifties with the speed of the aircraft increasing sharply (significantly more than the speed of sound), the demand for a more weight optimised performance, the fuel-efficient design and so on. The aluminium was stretched to its maximum limit. The search for newer and better materials was the only alternative. Continuous glass fibres, which were commercially available since "thirties, are found to be very strong, durable, ceaseless, non-flammable and insensitive to weathering. The glass fibres coated with resin can be easily moulded to any complex curved shape, especially that of a wing root and fuselage intersection and can be laid layerwise with fibres aligned in a desired direction. Fibreglass fabrics were successfully used in a series of gliders during the mid-fifties. The remarkable feature of all these gliders is that they exhibited superior flight performance and thus became the trend-setters in the use of glass fibre reinforced plastics.

Glass fibres are strong, but not stiff enough to use them in high speed aircraft. The search for stiffer fibres led to the development of advanced fibres like carbon, boron and kevlar. A host of structural grade synthetic resins were also commercially available. All these advanced materials provided the much-needed alternatives to less efficient aluminium alloy and fibreglass composites. The switch-over from the aluminium and GFRP to advanced composites in airframe construction was, however, very slow at the intial stage. It started with the design and development of a few composite control panels. In course of time, several structural parts such as horizontal stabiliser, vertical pylon, tail cone, canopies, fuselage, floor board, rotor hub and landing gears were developed with various composites, which later culminated in the development of several all composite aircraft and helicopters. Today the material menu of almost all aerospace vehicles including rockets, missiles, satellites, etc. are highly composite biased. The composite application in the aerospace industries is a process of continuous development in which newer and more improved material systems are being utilised to meet the critical design and flight worthiness requirements.

Fibre reinforced composites introduce the anisotropy (directional preference) to thermo-mechanical properties, which though eventually complicates the design/ analysis methodologies, is a desirable feature for design optimisation. In the cases of thin or moderately thick laminated composite structures, for example, wing skins, the lamina anisotropy can be effectively utilised to tailor the design. In the case of three-dimensional structural bodies, such as combustion chambers or rocket nozzle throats, fibre reinforcements can be provided in any arbitrary direction in a 3D space to resist forces acting along specific directions. Multidirectional reinforcement leads to increased toughness and damage resistance. It is,therefore, no wonder that fibre reinforced composites are widely employed in aerospace systems, and the major thrust is directed to develop design/analysis methodologies, fabrication processes and testing and evaluation techniques for fibre reinforced composites.

Polymer Matrix Composites

Currently fibre reinforced polymer composites constitute more than 90% (by weight) of the total composites used in aerospace industries. One of the major advantages of using polymers in structural composites is the ease of fabrication of complex structural shapes. Any aerodynamically efficient structural configuration, be it a wing or any other structural part, can be easily manufactured without involving difficult and expensive fabrication processes. The uses of thermosets such as epoxy and phenolics are very common with manufacturers of aerospace structures. Epoxy is favoured because of better strength and stiffness properties. Phenolics are recommended for high temperature applications. In recent years thermoplastics are found to offer a greater promise, primarily due to repeatability in their uses and repairability. The emergence of a couple of high performance thermoplastics like polymide, polyetheretherketones (PEEK), polyamideimide, polyetherimide, polysulfone, polyphenylene sulphide etc. has boosted their popularity. The reinforcements that are normally used in fibre reinforced polymer composites are glass, carbon, boron and kevlar. It is to be observed that these composites possess comparatively higher directional properties and lower densities than the conventional aluminium alloy, AA 2014-T6, that is commonly used in aerospace structures. It is to be noted that glass fibre reinforced plastics (GFRP) are very rarely used in primary structures, whereas carbon fibre reinforced plastics (CFRP) due to their superior stiffness and strength properties are used in many applications. Almost all structures of Beech Starship, Lear Fan 2100 and Voyager are made of CFRP. LCA also uses CFRP in the wing structure. Kevlar fibre reinforced plastics (KFRP) are usually preferred where the strength is the main design criterion. Boron fibre reinforced plastics (BFRP) possess excellent stiffness and compressive strength properties and, therefore, have great potential in aerospace applications. A lot of interest was shown in the late sixties and early seventies to exploit their full potential, but in course of time, their popularity dwindled due to difficulties faced during manufacturing of BFRP parts.

Metal Matrix Composites

Metal matrix composites (MMCs) exhibit extremely good thermal stability associated with high strength, ductility and toughness at a higher temperature. These characteristic features of MMCs are most desirable for design applications in aero gas turbine engines. The efficiency of an aero engine depends upon the turbine entry temperature (TET) of the gas stream, overall pressure ratio and gas path geometry under varying conditions of temperature and load, as the aircraft takes off, cruises and touches down. Thus the engine materials have to undergo combined effects of high temperature and severe stresses during engine operation. The primary requirement of a material, during such an arduous operation, is to maintain desired strength and stiffness without failing and/or deforming excessively so as to change the component geometry and thereby affecting the engine performance. Polymer based composites can not be utilised for engine parts due to limitation of their applications at temperatures higher than 450-500K. MMCs are suitable alternatives with aluminium, titanium and nickel alloys as one of the matrix materials and Al_2O_3, B, C, SiC and SiO_2 as one of the reinforcements. Aluminium alloys can be used to TET of 650K, whereas nickel alloys can be utilised up to 1200K. MMCs may be used in engine blades, combustion chambers, nozzle throats, exit nozzles, etc.

Ceramic Matrix Composites

The re-entry vehicles such as missiles, space shuttles, etc. warrant development of materials that should operate at temperatures higher than 1500K. The propulsion system of future aerospace vehicles also calls for an efficient, weight-sensitive design. The TET of these aero engines is likely to be raised to as high as 2000K. Under such situations, ceramic matrix composites (CMCs) are the only alternatives. Ceramics provide necessary strength at high temperatures and have considerable oxidation resistance. The matrices used in CMCs are glass ceramics, carbides, nitrides, oxides and borides. The reinforcements are Al_2O_3, B, C, SiC and SiO_2. Applications of CMCs are re-entry thermal shields and tiles, nozzles etc.

Carbon - Carbon Composites

Carbon-carbon composites are formed by multiple pyrolysis of a carbon fibre reinforced phenolic resin under pressure. Phenolic resin yields a high proportion of amorphous carbon char in absence of air. The material tends to be porous and must be reimpregnated to reduce the void content. Carbon-carbon composites are capable of withstanding very high temperature (>2800K) for prolonged periods with little strength degradation. However, oxidation takes place unless a thin layer of ceramic coating is applied. Three dimensional carbon-carbon composite blocks with multidirectional fibre arrangements can be fabricated thereby permitting fabrication of 3D machine parts with desired thermo-mechanical properties along specified directions. Prospective applications are nose cones of reentry vehicles, combustion and thrust chambers, nozzle throats, exit nozzles, leading edges of space shuttle, brake discs, etc.

Case Studies

A few case studies are presented here to emphasize the superiority of CMCs in high temperature aerospace applications. The analysis is based on the finite element analysis softwares specially developed by the author and his co-workers for the analysis of complex thermostructural problems.

A hollow infinite cylinder is internally exposed to heat flux q ($q=70\ W\ cm^{-2}$) while convective losses take place from the outer wall to the environment ($T_\alpha = 323K$, $h=0.15\ W\ cm^{-2}\ K^{-1}$). The stress-free reference temperature (T_{ref}) is assumed to be 323K. The inner and the outer radii of the cylinder are 2 and 6 cm, respectively. A 3D composite model with three different material systems, namely SiC-6061Al MMC, T75-nickel MMC and a typical carbon-carbon composite is chosen. The radial temperature distributions for the above materials are compared in Fig. 1. T denotes the outer wall temperature which is evaluated in each case as 478.55K. A drastic reduction in the radial temperature gradient occurs in the T75-nickel MMC. This can be explained by the fact that the conductivity of the rayon-based graphite fibres is 60 times higher than that of the SiC fibres. The CCC, based on a phenolic resin, records the lowest temperature gradient due to an even higher conductivity. The normalized radial stress variations ($\bar{\sigma}_r$) are illustrated in Fig. 2. High temperature gradients cause the maximum stresses to occur in the SiC-6061Al MMC. In comparison, the negative expansivity of the graphite fibres helps in producing extremely low thermal strains in the T75-nickel MMC and the CCC; the stresses are consequently lower.

A typical uncooled convergent-divergent nozzle is next considered. The environment immediately adjacent to the nozzle is assumed to be 393K. The nozzle cools by radiation losses from the outer wall. Two materials, SiC-nickel MMC and CCC are used as the nozzle material. The emissivity of nickel MMC is 0.2 and that for CCC is 0.5. The stress-free reference temperature is assumed to be 300K. Figures 3 and 4 illustrate the temperature and the stress variations. Here also it is observed that CCC has distinct advantage over its nickel MMC counterpart.

Conclusion

The current trend is to use the full potential of both MMCs and CMCs in high temperature aerospace applications. While substantial research and development have already been carried out in the last 3-4 decades in the area of PMCs, but the research and process development for effective use of MMCs and CMCs are still in its infancy. It is here NML in association with CGCRI, IIT KGP and other academic and research institutions located in the eastern zone can take the lead and provide directions.

References

1. S.M.Lee (Ed.), Int. Encyclopedia of Composites, Vols. 1-4, VCH, N.Y. 1990-92.
2. N.Mukherjee and P.K.Sinha, Thermostructural Analysis of Rotationally Symmetric Multidirectional Fibrous Composite Structures, Computer & Structures, 65 (6) (1997) 809-817.

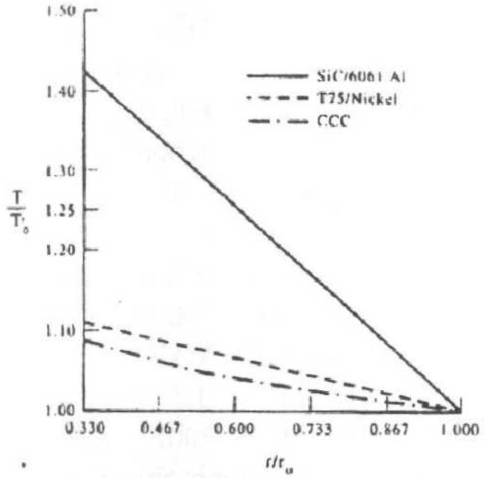

Fig. 1 - Radial temperature distributions in the hollow infinite cylinder for three different materials.

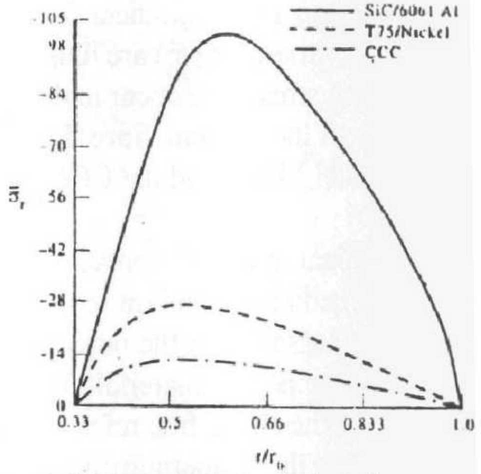

Fig. 2- Radial stress distributions in the hollow infinite cylinder for three different materials.

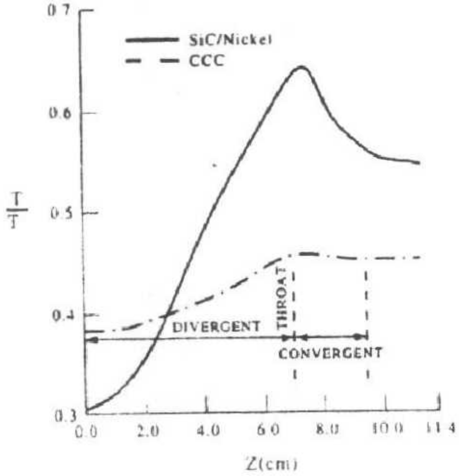

Fig. 3 - Comparison of axial temperature variations in the nozzle.

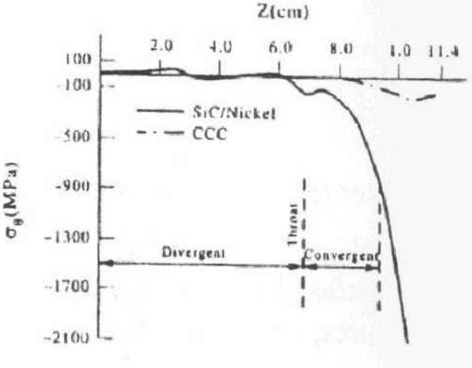

Fig. 4 - Comparison of the axial distribution of hoop stress in the nozzle.