4

Carbon fiber expands towards the twenty-first century

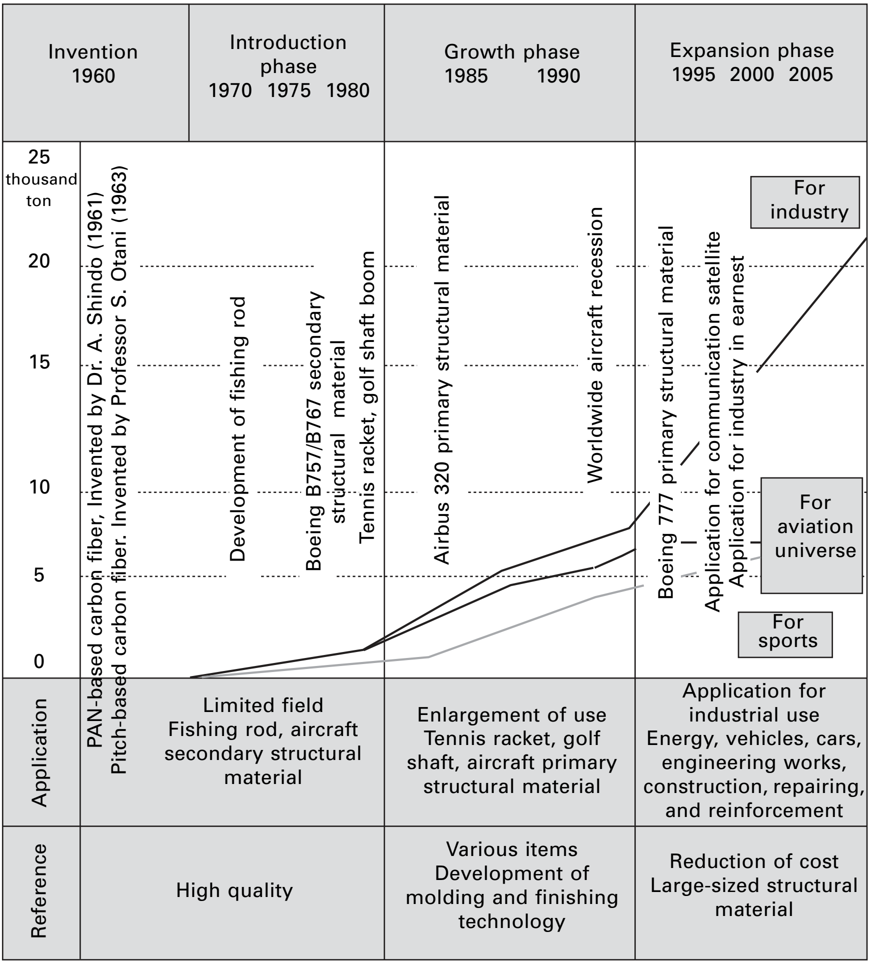
4.1 PAN-based and pitch-based carbon fiber lead the world

Carbon fiber was developed in Japan as a new material some 30 years ago. This fiber can be distinguished as polyacrylonitrile-based (PAN-based for short) and pitch-based carbon fibers. The main chemical component of carbon fiber is carbon, but the function of carbon fiber depends on the structure of the fiber. Using their unique properties, the application of carbon fiber is most pronounced in the superfibers category. Carbon fiber is used in Europe and the United States mainly in the aviation and space industries. It is the physical and mechanical functions of carbon fiber, which are harnessed in resources saving, energy saving, and protection against disasters. However, new biological applications have enabled their expansion into new fields such as control of aqueous environments. Moves to create thin, light, and strong fibers, can offer new areas of development to meet the needs of society. The changes in the global carbon fiber market are illustrated in Fig. 4.1.

4.1.1 Carbon fiber in high technology

PAN-based carbon and pitch-based carbon fiber, derived from pitch or tar as a byproduct of the carbonization of coal or in refining petroleum, have different applications. Pitch-based carbon fiber can be used for general-purpose products (isotropic) and high performance products (anisotropy). Carbon fiber is also classified according to the properties, whether high strength or high modulus fiber.

Generally carbon fiber is a conflux of thin fibers (filaments) with diameters of 5–8 microns. The conflux is called tow. According to the number of filaments in tows, it is classified 3K or 6K. K stands for 1000, 3K and 6K, therefore, mean 3000 and 6000 filaments, respectively. 3K and 6K tows are called small tows. On the other hand, large tows, with in excess of 50 000 filaments, have been produced recently to reduce the cost of production. The



4.1 Changes in the global carbon fiber market.

large tow is cut into 6 mm lengths, mixed with thermoplastic resin for reinforcement, and thus substitutes for 12K tow.

The production of carbon fiber can be compared to ‘charcoal making’, but of course it is not so simple. Wood is baked to charcoal over an intercepting air supply. However, fibrous PAN or pitch is processed at high temperature to carbonize. The difference between charcoal making and carbon fiber manufacture is that carbon fiber with different strength and moduli can be produced by changing tow materials and/or giving different heat treatment of the materials. The classification of carbon fibers is shown in Table 4.1.

Carbon fiber is not used on its own, but mixed with resin as a fiber reinforced material. This is called a composite material and is now one of the most important structural and heat resistant materials. The composite material

Table 4.1 Classification of carbon fiber

Classification	Species	Main application
PAN-based Pitch-based	High-performance carbon fiber	Advanced composite material
	Carbon fiber for general purposes	Insulating material Electro-conductive material
	Activated carbon fiber	Absorbent Electrode material for battery
Pitch-based	Carbon fiber developed in vapor phase	Electro-conductive material Electrode material for battery

made of glass fiber and plastic is distinguished as glass fiber reinforced plastic (G-FRP) from that made of carbon fiber and plastic (carbon fiber reinforced plastic, C-FRP). The first FRP, appearing in the 1940s, was G-FRP, and it was used in familiar household articles. In the 1960s, glass fiber and polyester resin were replaced by carbon fiber and epoxy resin, because of the higher performance and higher heat resistance, respectively. Currently it is a high-tech material, and is used in the field of electricity/electronics, medical care/welfare/care equipment, sports, leisure, aviation/space. More than 10 000 and 2000 tons/year PAN-based and pitch-based carbon fibers are produced, respectively. PAN-based carbon fiber is now established as a structural material.

It is noteworthy that both PAN-based and pitch-based carbon fibers were originally produced in Japan. PAN-based carbon fiber was invented in 1959 by Dr A. Shindo of Government Industrial Research Institute, Osaka (presently National Institute of Advanced Industrial Science and Technology (AIST)). It was first industrialized in 1971 by Toray. Mitsubishi Rayon and Toho Rayon (presently Toho Tenax) started manufacturing in 1983 and 1973, respectively. Pitch-based carbon fiber was invented in 1963 by Professor S. Otani of Gunma University (now Emeritus Professor of Gunma University), and it was industrialized as a general-purpose staple fiber in 1970 by Kureha Chemical Industry. This Japan-based technology is now used world-wide.

4.1.2 PAN-based carbon fiber goes around the world

In 1957–1958 the first rayon–based carbon fiber was produced in the United States, mainly from rayon. The Cold War which existed between the United States and the Soviet Union at that time drove the United States on to develop space technology and as a result there was a flourishing collaboration among industry, university and government bodies on carbon fiber research.

Barnebey-Cheney made carbon fiber derived from rayon fiber in 1957. Furthermore, National Carbon (an associated company of UCC) delivered carbon cloth to US air-force material research laboratory in 1958. In May 1959, this news was published by Nikkan Kogyo Shinbun, and Dr A. Shindo read this article and started work on making carbon fiber. In this way the PAN-based carbon fiber was manufactured. In autumn 1996, 37 years after the invention, Dr Shindo was decorated. He used many kinds of fibers to make carbon fiber, and finally he used 'Orlon' (a trade name for acrylic fiber made by US Du Pont) to demonstrate that PAN-based carbon fiber could provide high performance. It took only three months' research after reading the article for Dr Shindo to identify three important heat treatment steps necessary: flame-proofing (heat stabilization), carbonization at 1000°C, and graphitization at 2500°C. In 1959, a patent for 'method to produce carbon manufacture from polyacrylonitrile-based synthetic polymer' was applied for a patent, notified in 1962 and registered in 1963.

A report, 'study of carbon fiber' in the 317th report of Government Industrial Research Institute, Osaka was published in English in March 1961. As a result, a group at the Royal Aircraft Establishment (RAE) in Britain, initiated investigation into the application of composite materials in aircraft structures.

4.1.3 Carbon fiber used for impeller blade of jet engines

The National Research and Development Corporation (NRDC) was in charge of making a commercial scale production system using this new material. Courtaulds, the fiber company in the United Kingdom, Morganite, a research and development company in heat resistant materials, the Rolls-Royce Company, the manufacturer of jet engines and cars and the Atomic Energy Research Establishment (AERE), Harwell, UK joined to develop the material. All the British carbon fiber composite material in 1967 was made by batch cycle and thus the propeller blade of an engine was produced.

This propeller blade is blade of the rotor which is at the air intake of the aircraft engine. Unfortunately a bird flew into an engine made of carbon fiber composite material (RB-211) during the test, caused damage and as a result made the blade unusable in aircraft at that time. Subsequently, the design philosophy changed. Epoxy-resin replaced unsaturated polyester, and glass fiber was replaced by carbon fiber, and eventually in the latter half of 1960, a new type of engine (GE-90) was developed by American General Electronics. The engine, which mounted this blade, was made of carbon fiber that entered this field from 1967 to 1970. The news galvanized the acrylic fiber manufacturers.

Because the engine was considered as made of metal only until then, researchers working for acrylic fiber manufacturers were encouraged by the chance arrival of carbon fiber composite, and at one sweep, their entry into the field of carbon fiber began. Dr J. Matsui in charge of development of composite fiber (formerly of Toray) describes in detail the situation in those days in *Reinforcement Plastics*, vol. 43.

4.2 A step of development of carbon fiber

The nature of the demand for carbon fiber today has changed greatly from that of the days when carbon fiber was first developed. The full-scale global manufacture of carbon fiber started in 1971 by Toray, in 1973 by Toho Rayon (now Toho Tenax), and in 1983 by Mitsubishi Rayon. All the companies were acrylic fiber manufacturers. About 30 years passed already after Toray began manufacturing. The quantity of current world demand increased to about 20 000 tons in 2005. The demand suddenly grew about 1980, but weakened just before 1990, but again began to increase suddenly around 1994.

In this chapter, some representative PAN-based carbon fibers which could be used in the twenty-first century are described. PAN-based carbon fiber is merely described as 'carbon fiber' hereafter. Pitch-based carbon fibers are quite different and will not be discussed here.

4.2.1 Advanced composite material (ACM)

Carbon fiber is more often used as composite material than used alone. Composite material, in which carbon fiber is used as reinforcement fiber, is classified according to the associated material used in the matrix, whether resin, rubber, metal, concrete, or ceramic. Here, resin composite material which is much in demand is mainly described.

Matrix resin is divided into so-called thermosetting resin, which is stiffened when treated with heat, and thermoplastic resin. Epoxy resin is a representative thermosetting resin, and it is a main matrix material of C-FRP at present. The reason why thermosetting resin is used is that it is superior in specific strength and specific Young's modulus. Thermoplastic resin is used when keeping the main characteristic of the fiber at a maximum is the principal objective. The so-called super engineering plastics, PEEK (poly ether ether ketone) or PPS (polyphenylene sulfide) are used for this purpose. This material shows superior properties in reducing weight and in electroconductivity. Composite material is used to enhance the characteristics of the component materials, and so making up for their individual defects.

From ancient times reinforced composite materials could make a wall from reinforced plaster, with straw, wood and bamboo providing the fiber. Composite material currently has progressed from a simple combination to a high performance material using glass fiber reinforced plastic (G-FRP) in the first generation (1940 to 1960) and carbon-fiber reinforced plastic (C-FRP) in the second generation (1960 to 1980s). G-FRP was used for personal applications such as helmets and bathtubs; C-FRP was used for aviation/space material, and the use developed rapidly.

Application examples are shown in Table 4.2 in the fields of sports, leisure, aviation/space and general industry. The resin-based composite materials

Table 4.2 Application of carbon fiber in various fields

Field	Species of resin	Application	Properties	Application field
Sports/ leisure	CFRP	Fishing goods	Lightweight, rigidity, sensitivity	Fishing rod, reel
		Golf	Lightweight, rigidity, sensitivity	Shaft, head, face
		Racket	Lightweight, rigidity, sensitivity	Tennis, badminton, squash
		Ocean	Lightweight, rigidity, vibration retardation	Yacht, cruiser, boat for race
		Others	Lightweight, rigidity, vibration retardation	Bat, ski, ski pole, sword for kendo, bow, radio-controlled car, ping-pong table, billiards table
	CFRTP	Fishing goods	Lightweight, rigidity, corrosion resistance	Reel
		Golf	Lightweight, rigidity, design	Head, shoes
		Racket	Lightweight, rigidity, design	Racket
Aviation Space	CFRP	Airplane	Lightweight, fatigue resistance, heat resistance	Primary structural material: wings, tail assembly, main body
			Lightweight, fatigue resistance, heat resistance	Secondary structural material; aileron, vertical rudder, elevator
			Lightweight, fatigue resistance, heat resistance	Interior material; Floor panel, beams, lavatory, seat
		Rocket Artificial	Lightweight, fatigue resistance,	Nozzle cone, motor case
		satellite	Lightweight, fatigue resistance, dimension stability	Antenna, solar battery panel, tube truss structural material
General industry	CFRP	Car	Lightweight, high-speed, fatigue resistance	Propeller shaft, racing car, CNG tank
		Bicycle	Lightweight, high strength	Frame, wheel, handlebars
		Vehicle	Lightweight, rigidity	Rolling stock, linear motor car rolling stock, seat

Table 4.2 (Continued)

Field	Species of resin	Application	Properties	Application field
General industry		High-speed solid of revolution	Fatigue resistance, rigidity corrosion resistance, lightweight, high-speed	Centrifuge rotor, roller for industrial use, shaft
		Parts of electrical equipment	Lightweight, rigidity, vibration absorber	Parabolic antenna, speaker
		Pressure-resistant container	Lightweight, high strength	Hydraulic cylinder, cylinder
		Medical instrument	Lightweight, X-ray penetration	X-ray grid, surgical instrument, wheel-chair
		Engineering works/construction	Lightweight, corrosion resistance	Cable, concrete-reinforcing material
		Others	Lightweight, dimension stability, electroconductivity	Mold for resin, umbrella, helmet, plane heating element
	CFRTP	OA/office instrument	Rigidity, electroconductivity	Bearing of printer, cam, housing stand
		Parts for electronic/electrical instrument	Lightweight, rigidity, electroconductivity, high accuracy	VCR parts, CD parts, IT applications
		Parts of machine	Lightweight, rigidity, abrasion resistance	Bearing, gear, cam, bearing retainer
		Precision instrument	High strength, dimension stability	Camera parts, plant parts
		Others	High strength, vibration absorption	Sound speaker cone, glasses frame

CFRP: Carbon fiber reinforced plastics
Carbon fiber reinforced thermosetting plastics: Mainly used for materials requiring high tenacity and modulus
CFRTP: Carbon fiber reinforced thermoplastics
Carbon fiber reinforced thermoplastics: Mainly used for materials requiring lightweight and electroconductivity

need to have enough strength and dimension stability when they are used in daily life. However, heat resistance and abrasion resistance of these materials are not sufficient to be used in the next generation of supersonic passenger aircraft. But in recent carbon fiber advanced composite materials (ACM), it is their strength, rigidity, modulus of elasticity raised rapidly, which are in the forefront. When an aircraft is lightened using ACM, flight performance and fuel efficiency increase. Inevitably then, an increasing quantity of carbon fiber will be used in aircraft serving to increase size of future aircraft. The same thing will occur in the space sector, since reducing the weight leads to energy saving. On this account, aluminum alloys or light metals are reinforced with carbon, boron, silicon carbide fiber, and thus metal-based composite material can be developed to make lightweight, heat resistant, and abrasion resistant material, possessing superior properties. Boron fiber reinforced aluminum which first appeared around 1980 is a metal-based composite developed as a third generation material. It was used as a structural brace for the fuselage of the space shuttle and as a car component plunger because of its superior heat resistance. It is also going to be used for the development of the Orient Express ‘super sonic transport’ linking New York and Tokyo in the future. In this way, the development of composite materials from the first generation to the third generation is accompanied by a high performance and a high price. However, a price will be naturally reduced if applications spread, and it can be mass-produced.

Advanced composite material (ACM) such as (1) resin composite material, (2) metal composite material, and (3) ceramic composite material are currently the main products. Resin-based advanced composite material can be made by autoclaving and molding the layered intermediate material (prepreg) by impregnating carbon fiber with high strength and high modulus epoxy resin. This material is lightweight, has strength and resilience which exceeds that of aluminum alloys, but remains more expensive than aluminum alloys.

4.2.2 Applications in fishing rod, golf and tennis in Japan, and aircraft/space in Europe and the United States

Originally the golf shaft was made of steel. Then came glass fiber. Carbon fiber is superior to glass fiber in its vibration damping. For this reason glass fiber was replaced by carbon fiber comparatively early. The technique of making a fishing rod with carbon fiber was applied to a golf shaft, because the properties required of golf shafts were to be light, thin, minimum torsion, durability, feel of the driven ball, and a long carry. The properties of golf shafts thus improved quickly and the so-called ‘black shaft revolution’ started. The demand grew rapidly in the early 1970s.

In 1976 application to the tennis racket started and Kawasaki Racket produced rackets in Japan. At that time the share of goods using carbon fiber rose to 70% in the field of sports and recreation in Japan. Among them, fishing rods, golf shafts and tennis rackets consumed 90% of the production of carbon fiber (see Fig. 4.2).

As the material has high physical properties such as specific strength, specific Young's modulus and high reliability, freedom of design made it possible to develop materials with new performance which was impossible with conventional materials.

In the later half of 1970s, carbon fiber begun to be used in airplanes and for munitions in Europe and the United States. Export of munitions was not allowed in Japan at that time. Accordingly the demand for carbon fiber changed from military jets in the latter half of the 1970s, to private passenger aircraft in the 1980s.

4.2.3 Application to commercial aircraft cabin

The development of a commercial aircraft cabin takes about ten years. Boeing began to use carbon fiber in its 757 and 767 type planes during 1975 to 1980. Lightening of an aircraft by using composite material is shown in Fig. 4.3. There are two ways of using carbon fiber in aircraft. One is in the primary structure, and another is as secondary structural material. Primary structural materials are used for parts such as main wing or tail assembly. The secondary structural materials are used for parts such as floor and other internal sections and operating systems.

Subsequently the European airbus (Airbus Industries) adopted C-FRP for their primary structural materials (vertical tail). Ironically, a much higher technology is demanded for private passenger aircraft than for military aircraft. Construction of private machines comes close and here the demands are severe in achieving the necessary safety factors.

The United States increased armaments expenditure after the attack on Afghanistan by the Soviet Union in 1982. Then there was a great increase in use of carbon fiber which spread swiftly into the sports market. Demand forecasting of PAN-based carbon fiber is shown in Fig. 4.4.

4.2.4 CF composite material specification announcement for 'Boeing 777 type'

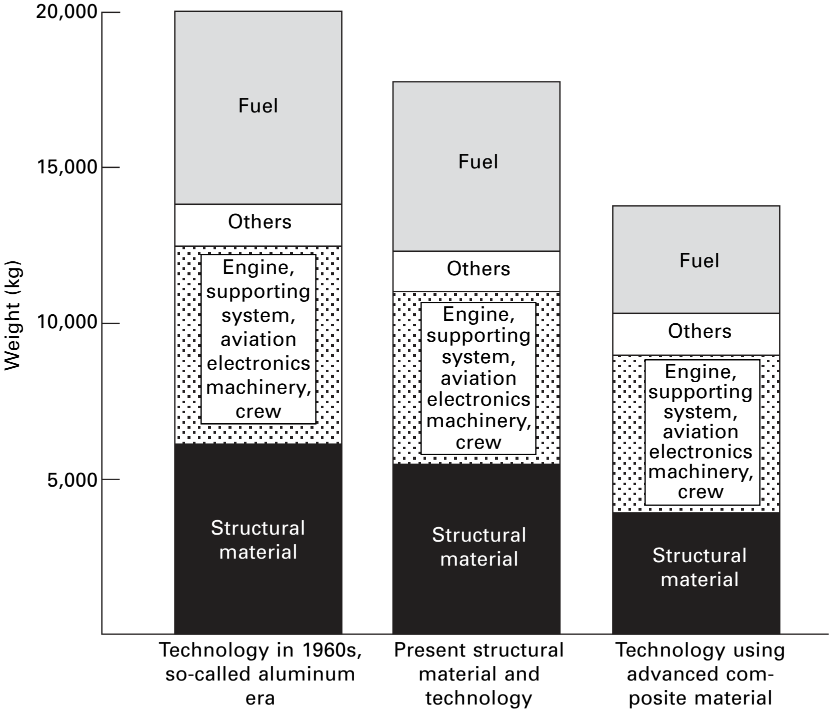
Boeing, in particular, decided to use carbon fiber composite material in the primary structure of passenger aircraft, and 'a specification for carbon fiber composite material to use to Boeing 777 mode' was announced to material manufacturers throughout the world. They identified the characteristic material necessary for aircraft, and progress of the carbon fiber composite material which was usable as primary structural material was achieved.

Fishing rod appeared in the first half of 1970

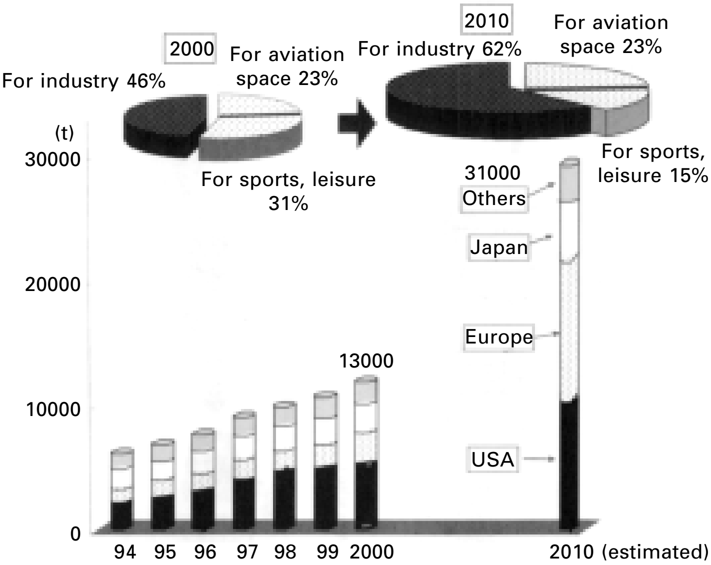
Tennis racket appeared in the latter part of 1970

Black golf shaft appeared around 1973

4.2 Three main uses of carbon fiber (Daiwaseiko).



4.3 Lightweight aircraft made of composite material (New material user's book).



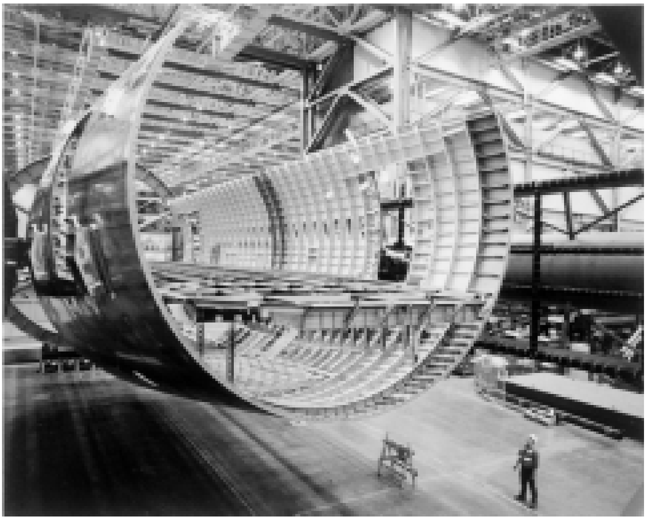
4.4 Demand prediction of PAN-based carbon fiber.

Carbon fiber composite material prepreg ‘P-2302’ from Toray was authorized for this work in 1989. This development took about ten years. In 1995, 13 tons, at a use rate of 15%, of carbon fiber composite material was used to make one Boeing 777. The material was used for the floor beam and part of the tail assembly. In this way the weight of the horizontal tail of the Boeing 777 type plane decreased by 25% and that of the whole tail assembly by 15% compared with the corresponding use of aluminum alloy. The assembly plant of the Boeing 777 and the implementation are shown in Fig. 4.5.

4.2.5 The American ‘black shaft’ main jib

In 1990 an entirely new quality of carbon fibre was developed, meeting, for example, the demands of supersonic aircraft. The development work took place from 1986 to 1987 as the reduction in the tension in the Cold War reduced the demand for carbon fiber in ammunitions. This did not affect Japanese manufacturers directly. However, European and American manufacturers faced big problems, despite the growth in sports and private plane applications for they had greatly increased their production capability. Therefore, the relationship between supply and demand grew out of balance. There was a large recession in airplane construction.

Thus the demand for carbon fiber as a high technology material decreased sharply. But this was only temporary and shortly demand increased again. It was carbon fiber used for the black golf shaft in about 1992 which started the



4.5 Carbon fiber composite material used for floor girder material of Boeing 777 (Boeing).

rejuvenation. The black shaft boom started in Japan, but was slower in the United States. There are reasons for the development of the market.

One professional golfer offered an opportunity

In 1992, 20 years later than in Japan, the carbon fiber golf shaft came into the mainstream in the United States. It started with the professional golfer, Davis Love III, who used a golf shaft made of carbon fiber when he won the US Open Championship. It was Gay Bruier, who used the black shaft when he won the championship at Pacific Ocean Club Masters in 1972 that started the fashion in Japan. It helped also that the price of carbon fiber had fallen dramatically in the latter half of 1980s to 1990. It remained extremely expensive in Japan, so when the carbon fiber golf shaft boom came to the United States, the lower price had an adverse effect on prices in Japan. The black CF shaft was easy to use and as the price became comparable to conventional shafts their popularity increased. It became the savior of the carbon fiber manufacturers at that time. It was expected by the Japanese carbon fiber industry in 1993–1994 that equipment for Boeing 777s would be made using carbon fiber. However, the recession in the aircraft industry lasted into 1995 and 1996.

Industry applications begin to spread

In 1990 applications, for aviation/space and sports were about 40% each, and, industry generally, it was only around 20%. Carbon fiber composite material used in sports and recreation is shown in Fig. 4.6. The share of C-FRP was 50%, 27% and 23% for industry, sports, and aviation/space.

New industrial applications began to develop in about 1992–1993, particularly in the field of engineering works/construction. Its use as a repairing material also began to grow.

4.2.6 Two major characteristics of carbon fiber

Development of a ‘strong fiber’ was the dream which fiber engineers pursued. Carbon fiber can be classified by its mechanical properties. There are two representative characteristics: tensile-strength and elastic modulus. Tensile strength is expressed by grams needed to run out 1 denier fiber pulled from end points. Centi Newton per Deci tex (CN/dtex) is used internationally following the International System of Units decision in October 1999. Grams per denier unit was used previously. Elastic modulus indicates degree of hardness. The larger the value, the harder the material. What was not expected was the added strength which carbon fiber provided to fiber reinforced composite material. The nature of this effect depends on the type of carbon fiber. So every company developed various kinds of carbon fiber.

4.6 Carbon fiber composite material used in ski and ski-poles.

In the mid 1980s Toray developed 'T-1000' which has a maximum strength of 630–640 Gpa. For parts of an airplane, a higher strength is demanded than the high elastic modulus. Development emphasis was on 'how to increase strength'. To achieve this, it is necessary to make a fiber with less solid state defects in the graphite structure. Generally, to produce carbon fiber, the process involves baking of feedstock fiber under strain at 200–300% in air for about ten minutes. Then the temperature is increased to 2000°C at the rate of 1000°C over several minutes in an inert atmosphere. When fiber with high elastic modulus is burnt at about 3000°C, in nitrogen or oxygen the acrylic fiber can be converted to a carbon fiber having a graphite structure without defects and hence is very strong. This is treated to have properties like C-FRP.

4.2.7 Japanese enterprises started from acrylic fiber

The reason why three carbon fiber manufacturers in Japan (Toray, Toho Rayon (now Toho Tenax), and Mitsubishi Rayon) are strong in carbon fiber production is that they produce acrylic fiber as a starting material. Courtaulds in the United Kingdom and BASF in the United States withdrew from carbon fiber manufacturing in 1990 and 1993, respectively. Amoco and Hexcell in the United States are companies who are good at carbon fiber production technology. Therefore, they produce or buy acrylic fiber only in small amounts. In contrast Japanese manufacturers developed their manufacturing from acrylic fiber and so achieved an overwhelming share of the world market.

4.2.8 Material development

Since carbon fiber seemed to have little practical use initially, universities did not have it in their materials laboratories. It was always compared to metals and its value and strength in composites was not recognized. So it was left to business to undertake the fundamental developments.

Superfiber is currently superior to metal and within a multi-component composite material could be leading the material revolution in the twenty-first century. Such materials are worthy of study by universities.

4.2.9 Space developments are connected directly with weight and price

In the field of space exploration the weight of the material is related directly to the price of the operation. For example, an artificial satellite is launched using a Saturn rocket, so if the weight can be reduced there is a price and engineering benefit. Japan entered commercial space exploration with H II type rocket. Since 19 billion yen is required to launch one satellite, the target is to reduce the price by about one-third. When composite material is selected, one of the main constraints is service temperature. According to the Ministry of Trade and Industry (MITI), the body surface temperature increases to around 250°C by aerodynamic heating during supersonic transport (SST) at Mach 2.5, to fly Tokyo to Los Angeles in four hours. The National Space Development Agency (NASDA) failed in its attempt to launch the DH II rocket (No. 8) in November 1999, and Institute of Space and Astronautical Science (ISAS) of the Ministry of Education and Science failed to launch M – V rocket (No. 1) in February 2000, because of abnormality of the number one stage engines. The price of the operations ranged up to 10 billion yen.

Carbon fiber composite material with high modulus has good thermal conduction, and thermal expansion is almost zero. Therefore it is used in radio antennae to contact ground masts. In addition, carbon fiber is used within storage sections of the space shuttle and in the manipulator for its remote control.

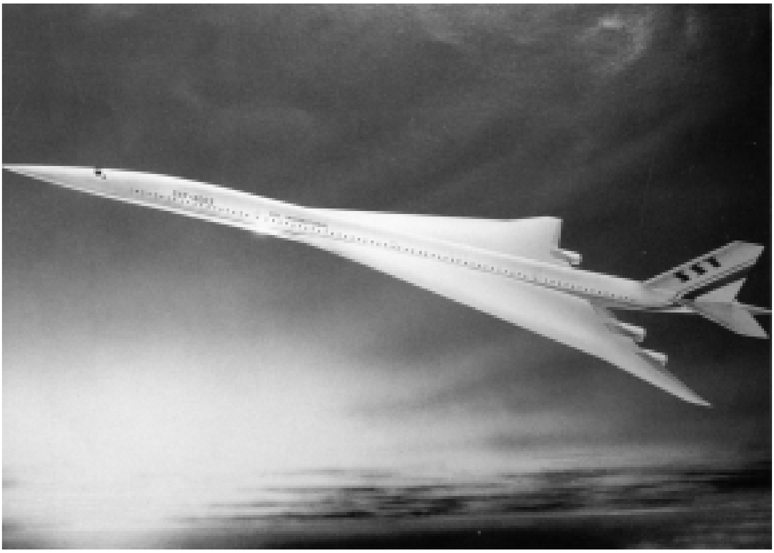
4.2.10 Development of supersonic transport (SST)

Work in Japan has started on the next generation of supersonic transport. Manufacturers will work on the body and the National Aerospace Laboratory will collaborate with research organizations for the propulsion systems. It is anticipated that the SST which incorporates carbon fiber composite material can overcome the problems which have been associated with the supersonic plane Concorde, and coexist with other aircraft and the global environment. The hope is that the advantages to the life of the nation and the economy will spread globally and contribute to the same extent that new trunk rail transport of Japan has. The planned SST has a capacity of 250–300 seats, cruising speed of Mach 2.0–2.4, and a flying range of 9300–11 000 km. Development research is ongoing, and flight model developments are expected around 2005.

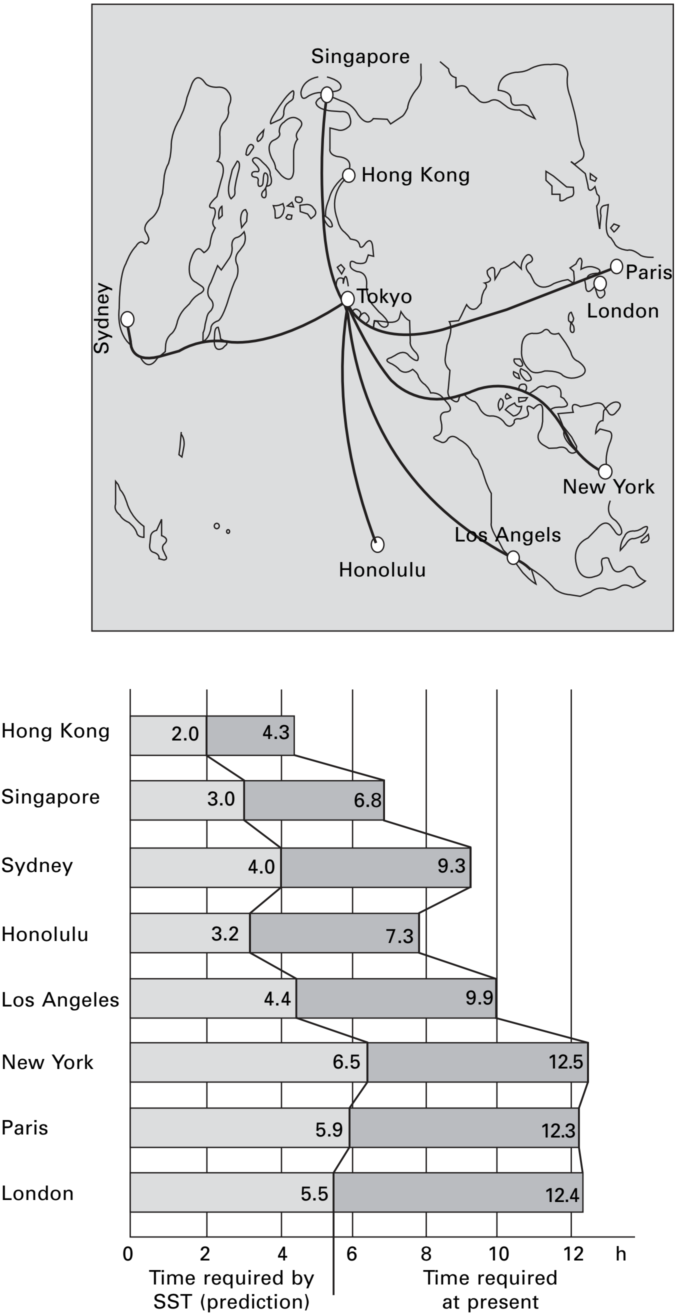
The development of next generation supersonic transport (SST) is shown in Fig. 4.7, and the one-day travel zone in the world is shown in Fig. 4.8 when SST is finally developed. The vision is to travel from Tokyo to New York in two hours.

The airplane would take off from a normal runway, and rise into the sky. The Pacific would be crossed at Mach 8 (8 times the speed of sound, 9000 miles per hour). The race to journey from Tokyo to New York in 7 hours, half of the present 14 hours, has started. Sixty per cent of material used for such a supersonic transport will be composite material, including both organic and inorganic materials, and the base material is carbon fiber.

The development of a new type of engine is being pushed forward separately. The materials used must have exceptional heat resistance, since supersonic transport lifts off vertically and enters into the stratosphere immediately. In



4.7 Development of supersonic transport for next generation (The Japan Society for Aeronautical and Space Sciences).



4.8 One-day air travel ranges from Japan using new generation SST (Japan Aviation Space Engineering Society).

addition, when it enters into the stratosphere there could be the problem of ozone layer depletion. There is no meteorological change in the stratosphere in the range of 10–55 km from the surface of the earth. The wind blows with uniform orientation, and the air temperature is maintained almost constant. On this account the automotive exhaust gas must be minimized so that an environmental problem can be settled.

Over the past 30 years, the nature of the base resin of composite material changed from epoxy resin with heat resistance of around 150°C to polyimide resin with heat resistance of about 300°C. However, this is not enough to be used as the structural material, because heat resistance of 500–900°C is required for hypersonic transport at around Mach 5. For SST materials high heat resistance and tenacity are necessary, so that new resin must be developed. The development of such materials has already started. In the development of the A380, a super large-scale aircraft with 500 passengers to be developed by Aerospacial by 2005, lightening of the aircraft using composite materials is the key point of its success. In the A380 C-FRP will be used as the main secondary structural material for the vertical tail fin, tail plane, tail cone, main wing, floor beams, floor panels, strut to support floor, and composite material for cockpit and body. The trial to reduce cost and to introduce new molding technology is now ongoing. The A380 is shown in Fig. 4.9.

4.2.11 Expansion to geotextiles

After the enormous earthquakes in California, Osaka-Kobe-Awaji in Japan, and Taiwan, the demands for PAN-based carbon fiber for industry application,

4.9 A380, a super large-sized passenger plane with 500 seats, to be developed by 2005 (By computer graphics, Airbus Japan).

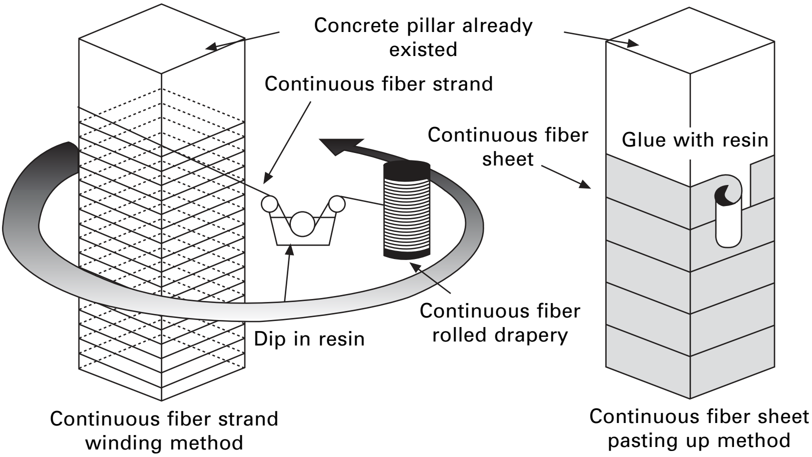
especially in engineering works and construction, have grown quickly. The necessity of strengthening commercial buildings and bridge piers has increased the demand for carbon sheet and cloth. Recently, the market for industrial applications, especially in engineering works and construction, accounts for 50% of carbon fiber production.

Nowadays high performance fiber, including carbon fiber, is used as a replacement for iron materials, particularly where rust and etching are a problem. Using this material also allows a reduction in manufacturing and maintenance repair energy. While with iron, the material is cheap, labour costs are high because of the difficulties in fabricating iron plates at the site and the heavy weights involved.

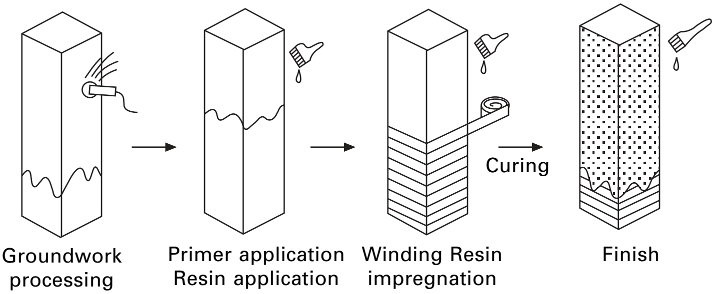
However, carbon fiber is soft, light and strong in composite with resin. After incorporating carbon fiber into a bridge pier, for example, and fixing with resin, the pier becomes very strong and able to withstand earthquakes. The material may be expensive, but the labour costs are less. Moreover, carbon fiber is light so that it does not overload the original pier. So this construction method now attracts attention. Therefore the quantity used for repair/strengthening in engineering works has increased very much. Examples of its execution and mechanism used are shown in Figs 4.10 to 4.14. It is the reason why the demand for carbon fiber in engineering and construction grew so quickly around 1992–1993.

4.2.12 The first building in the world to use a space truss made of C-FRP

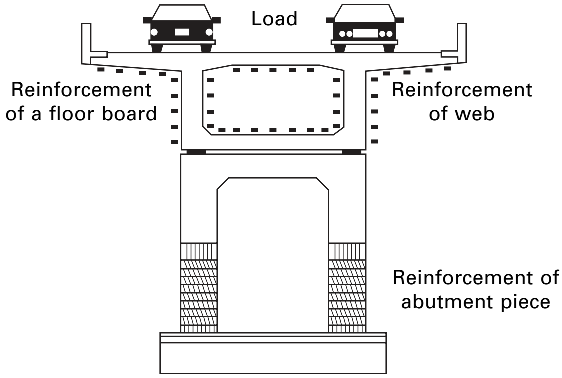
In the construction of the dining room of the Toray Ehime factory, the roof space truss made of C-FRP which can be lifted in one piece. The space truss



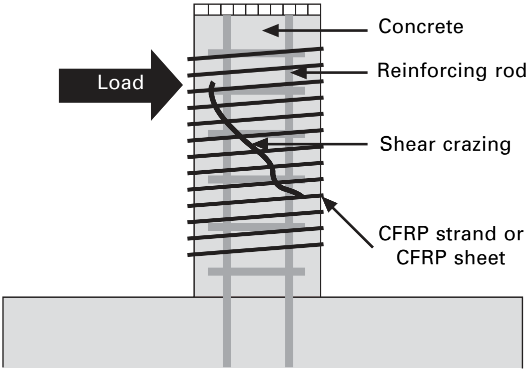
4.10 A continuous fiber sheet pasting up method and continuous fiber strand winding method.



4.11 An execution procedure of a continuous fiber sheet and tape pasting up method.

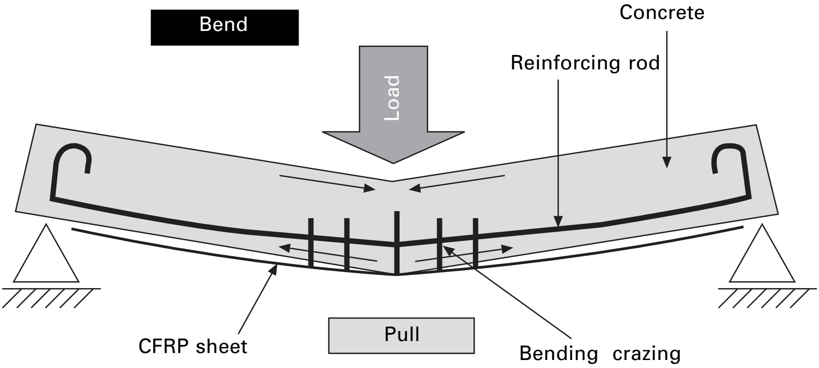


4.12 Reinforcement of a bridge.



4.13 Mechanism of shear strength reinforcement.

roof is shown in Fig. 4.15. This truss is composed of a triangle and tetragon made of C-FRP. The truss is 1/30 000 in weight of the structure, superior in corrosion resistance, and the same or greater in strength compared to that



4.14 Mechanism of bending strength reinforcement.

4.15 A view of Toray Ehime factory dining room where a solid truss roof made of CFRP was used for the first time (Toray).

made of iron or steel. In addition, it could be built effectively and safely in a short time and the design is geometrically beautiful. Such a space truss made of C-FRP was developed jointly by Toray, Shimizu Construction, and Nippon Aluminum after getting authorization from the Minister for Construction. Six workers made the space truss roof with manual operation in four days, assembling 800 lightweight main parts.

Two 50 ton cranes used in usual construction work were used, and they lifted the parts to about six meters from the ground, and it was installed in units of ten steel columns. The duration of the operation was about 30 minutes. If the same scale roof were constructed using an iron space truss, two 100 ton cranes with a gross weight of 18 tons would be necessary. Such a space truss will be used extensively for building indoor pools and gymnasia, etc. in the future.

4.2.13 Application for clean energy

Wing for wind power generation

In the United States and Europe, there are many wind power generation facilities which harness clean energy. At the end of 1999 there were more than 200 power generating windmills in Japan. However, there are few places where the wind blows uniformly all through the year. Because there are many islands in Japan, wind power generation is attractive and is being examined for regions where transmission of electricity is not easy. Table 4.3 shows an international comparison of the quantities of wind power/solar power generation. In wind power generation, a propeller is moved by the wind. Thus toxic waste gases such as nitrogen and sulfur oxides are not produced as in thermal power generation by combustion of coal or petroleum. An example of wind power generation is shown in Fig. 4.16.

Only a few places are suitable for power generation because of the need for maximum wind power. Tomamai and Shiribeshi towns in Hokkaido and Tappimisaki in Aomori prefecture are such locations and attention to this form of energy is now being given by local government and private companies.

The CRC in Tokyo, using meteorological data from the Meteorological Agency, has developed a system for predicting wind velocity in every direction

Table 4.3 Comparison of wind and solar power generation (capacity of facility (1000 kW))

	Wind power	Solar power
Japan	38	133
Germany	2579	54
USA	2055	100
UK	474	1
Netherlands	425	6
China	294	–
Italy	155	18
Switzerland	–	12
World total	9841	392

NEDO (New Energy and Industrial Technology Development Organization)

4.16 Wind power generation.

and consequently calculating the potential electric power generation. A great deal depends upon the generating efficiency of a blade itself. For this reason, lightweight wings are requested. Thus wings made previously of G-FRP are now being replaced by C-FRP.

Strengthening of natural gas storage tank

Each State in the United States can have its own regulatory systems. Exhaust gas regulation is one example. As a result there are States where exhaust gas regulation is so strict that cars using gasoline are severely hampered. There cars using natural gas became popular. There are many advantages. Natural gas is cheaper and reduces the quantity of harmful exhaust gases. The situation is similar in Canada. In Japan liquefied natural gas is imported from the Near and Middle East and delivered to each house through a pipe in the form of gas. In the United States, it is produced in large quantities and there is no need to liquefy, so that it is comparatively cheap. To transport in gaseous form a strong gas tank is required. An iron gas tank reinforced by carbon fiber is used for this purpose, and is shown in Fig. 4.17.

If all cars in the United States and Canada are eventually converted to use natural gas, the market will become very big.

Natural gas cylinder on the roof

4.17 Natural gas car.

4.2.14 Safety-related fields

Firemen carry a storage tank on their backs for breathing air when fighting a fire, in the way a diver carries an aqualung. Thus the tank for a fireman should be strong and light, and for this purpose carbon fiber is used. To reinforce such a tank about 1 million tons/year CF is now used globally.

Teijin uses lightweight FRP composite for the container tank for firemen and patients at home who need an oxygen cylinder. The company extended its use of natural gas container tanks to small-sized commercial vehicles in 1994, and to low-level Tokyo buses in spring 2000.

Lightweight ‘Ultressa’ which can lifted by a child is shown in Fig. 4.18. ‘Ultressa’ is made from a seamless, high strong corrosion resistant aluminum alloy reinforced with epoxy-resin impregnated glass-fiber, and is half the

4.18 Lightweight air-breathing device made of CFRP (Teijin).

weight of an ordinary iron container. The container, in which glass fiber is replaced with carbon fiber, is 30–40% lighter.

4.2.15 Application in other fields

Beds used for CT (computed tomography) scanning

Recent medical technology has witnessed a marked enhancement, not only in diagnosis techniques, but also in the equipment used. The CT scanning bed using carbon fiber is one example. Previously, the bed was made of wood or plywood, covered with thick, white cloth to cushion the skin.

Carbon fiber is used instead of wood because of its better X-ray permeation than wood. Polystyrene foam covered with carbon fiber is used and is much less a burden for the human body and clearer X-ray photographs are obtained. The X-ray transparency of carbon fiber is about 10 times greater than aluminum and wood, and on this account carbon fiber is now introduced in such medical X-ray equipment. Carbon fiber is used for most CT scan beds now, and the quantity of carbon fiber used in this field is 100–200 tons per year.

Lightening of various rollers

Roller used for printing machines used to be made of metal. The use of carbon fiber has revolutionized the production of the roller in these operations such that they can be managed by one or two people and the danger of handling heavy rollers has decreased. Carbon fiber is also used for rollers in other fields.

Challenge for America's Cup (2000)

The yacht used in the America's Cup races had a coxswain of 24 m, a maximum width of 4.5 m, a displacement of 23 t, and huge mast of 34 m in length. The development of new craft was designed to give a lightweight and well-balanced hull and mast. The planning was undertaken by Professor H. Miyata of Tokyo University with a team of 30 researchers from the best marine engineers from five universities and five companies. They spent four years and one billion yen to develop the new craft. They combined leading shipbuilding techniques with seeking new lightweight materials. The result was JPN44 (pet name of Ashura) which performs well in strong wind and the lighter JPN 52 (pet name of Idaten), a narrow-width craft which can move fast in light breeze conditions. Yachts which challenged in the Americas' Cup are shown in Fig. 4.19.

CFRP aramid honeycomb sandwich structure materials were used for the hull, and CFRP and aramid composite used for the mast, boom, and spin pole. The manufacture of the hull was undertaken by Nippon Challenge Building, made up of invited public participants. The Japanese team finished fourth in the preliminary race, and the CFRP technology was proven in a global arena.

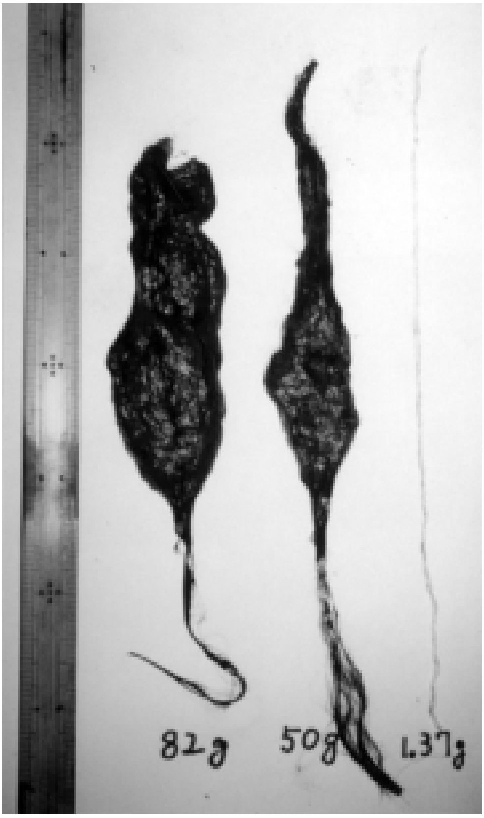
4.2.16 New applications in the field of aqueous environment

Ecology, aiming at harmonization with nature will be important in the twenty-first century. Applications of carbon fiber to aqueous environments can assist here. For this reason the Ministry of International Trade and Industry (MITI) started their carbon fiber-aqueous environment project in this field. Carbon fiber in water can collect large quantities of microorganisms which can decompose soap (carbon source) and domestic sewage (nitrogen source). In this way microorganisms grow to form large colonies, which can purify

4.19 Yachts challenging for America's Cup (Mitsubishi Rayon).

wastewater quickly. A direct purification experiment in a river is shown in Fig. 4.20.

Professor A. Kojima of Gunma National College of Technology first observed this phenomenon which led him to utilize resources and techniques of the textile industry to conserve the aqueous environment. How does carbon operate in this way? Professor M. Matsuhashi of Tokai University discovered that an extremely weak signal is given by carbon, which revitalizes a nearby cell which then grows. The subsequent colony of grown cells send stronger



4.20 Purification of river water by microbe adhered on carbon fiber (Professor A. Kojima of Gunma National College of Technology).

signals which proliferate even more cells. By using his study, relations between microorganism anchoring, propagation and good algae field formation were understood. The surface of carbon fiber becomes covered with a gel-like material which is secreted by the microorganisms or protozoa. Carbon-loving microorganisms anchor and grow. This anchoring and proliferation are promoted by electromagnetic wave promoted by the graphite structure of the carbon fiber.

Algae form within the field of carbon fiber as microorganisms anchor to the monofilament of carbon fiber in large quantities. As carbon fiber moves like waterweed because of its high modulus and large elastic recovery, fish are convinced that carbon fiber is a waterweed. So fish lay their eggs willingly, and a living circulatory system is produced in a naturally occurring form. This phenomenon has never been observed by any other traditional fiber materials, but is well known for natural waterweed. Even when large quantities of microorganisms anchor on to the carbon fiber, water from outside can penetrate into the carbon fiber and microorganisms can continue growing due to the movement of carbon fiber. Professor S. Ohtani, the project leader called this phenomenon the ‘net pump action’.

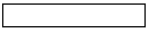
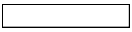
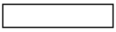
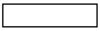
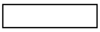
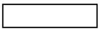
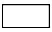
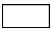
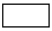
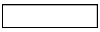
This finding is useful for the purification of water and replanting in desert regions, leading to effective resource and energy saving. Comparing this method to a chemical purification method demonstrates that it is much more eco-friendly. Microorganisms anchoring to carbon fiber have now been observed in rivers, marshes, ponds and domestic sewage. The experiments have also progressed in desert replanting and in the gathering places of fish in the sea. Tests have been repeated in Australia, China, India, and Thailand.

Textile companies in the Kiryu district produce carbon fiber and cloth, knit, and their combination for these developments. The market is big and carbon fiber is set to replace ordinary water purification systems.

4.3 The future of PAN-based carbon fiber

Table 4.4 shows the application of carbon fiber in sports in Japan and the US market, but developing more slowly in Asia. For aviation/space, expansion along the Asian route and ultra high capacity passenger transport airplanes is

Table 4.4 Development of carbon fiber application in 21st century (Toray)

Usage	Item	Example	Growth rate/year (%) 10 20 30
Industry	Container for high pressure gas	CNG tank, air-breathing device	
	Engineering works/construction	Reinforcement of abutment piece, construction material	
	Transportation device	Boat, truck, car, train	
	Energy	Flywheel, windmill	
	Parts of machine etc.	Roll, pipe, container	
		Compound, medical instrument etc.	
	Others		
Sports	Golf	Carbon shaft share 60% →	
	Racket	80%	
	Fishing	Developed in Japan and USA	
		Developing in Asian countries	
Aviation/ space	Aircraft space satellite	Super jumbo aircraft HSCT (high speed commercial transportation)	

expected. Most growth is expected in industrial fields such as high-pressure vessels, engineering works/construction, transportation and machine parts. The application developed by NASA and DALPA will be used in energy-related fields. The application of carbon fiber to cars, boats and vehicles will have enough advantage because carbon fiber is light. In France, they experiment to replace iron as the core with carbon fiber to make a lightweight electrical wire. Furthermore, carbon fiber can show the same electroconductivity as silver, when a chemical compound of chloride is introduced inside. It can therefore contribute to energy saving.

Carbon fiber utilized as reinforcement of concrete poles and durability strengthening of buildings following the Osaka, Kobe and Awaji great earthquake disaster have contributed greatly to energy saving. The centrifugal separation device for enriching uranium (revolution drum) for nuclear applications is now made of composite material in Europe, and concentration of the fuel can now be carried faster. The polar plate of fuel cell is now also made of carbon fiber.

In addition, resource mapping satellites are made of carbon fiber composite material as in windmills and tendons in oil rigs to probe oil fields. Secondary lithium cell cathode materials, super-high-speed energy storage equipment will also use carbon fiber. Japanese manufacturers have a 70% and 90% share of PAN and pitch, respectively, and could be the leading producers.

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