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Research and development for environmentally conscious smart composites

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Research and development for environmentally conscious smart composites

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Abstract—Advanced composite materials (ACMs) such as carbon fiber reinforced plastics (CFRP) have a high specific strength, rigidity and the advantage of being able to be designed to meet specific requirements. ACMs have been extensively developed and applied to a wide range of industrial fields including aeronautics and astronautics, ships, vehicles, civil engineering and architecture, sports and recreational articles.

Off-setting these various advantages, ACMs also have detrimental effects which may be harmful to the global ecological system after the end of the product life.

A recent trend of research and development of composites, the so-called SPAGHETTI syndrome, tends to add more functions to ACM, consequently making constituent materials more diversified and complicated. Some experts point out that, under present circumstances, this may produce more man-made garbage which is hard to incinerate or recycle and finally result in devastation of the ecological system.

This paper places special emphasis on original composites compatible with the requirements for recycling as a design prerequisite. A concept of environmentally conscious, smart composite materials which are able to satisfy various functional requirements and impose fewer hazards for the global environmental system is introduced.

Keywords: Environmentally conscious smart composites; bionic design; closed-loop recycling; intelligent function; recycling function.

1. INTRODUCTION

The development of materials can be divided into five generations, as with computers [1]. The starting point of composite materials was around the 1940s when glass fiber and unsaturated polyester resins were industrialized and fiber reinforced plastic (FRP) was utilized for the first time. Now, over a half century later, we are in a transition period from the fourth to the fifth generation. The first generation (up to about 10 000 years ago) was the stone age when people used natural materials and just modified their shapes. The second generation opened during the Jomon period in Japan (about 9000 years ago), when people extracted useful components from raw materials and processed them. In this generation, methods of smelting copper, bronze and iron were developed and this continued up to the Industrial Revolution. In 1907, Bakeland succeeded in synthesizing phenol resin (Bakelite), producing a material which did not exist naturally. This was the opening of the third generation. The materials from the first to the third stages were all monolithic, macroscopically homogeneous and isotropic. In contrast, the materials of the fourth generation, in which FRP was born, feature characteristics that can be modified to suit the purpose. Now we are in the age of composite materials, the performance of which can be designed according to requirements.

In the forthcoming fifth generation, material characteristics are not constant over time but become soft or hard in response to external stimulation. These materials are called intelligent materials, and the objective of material development in the 21st century, as well as success in their utilization, may be called a 'material revolution'.

Recently, global warming and desertification caused by mass consumption and wasting of energy and products have become serious problems. The preservation of our earthly environment is now a common matter of concern related to survival of the human race. In this phase of material development, production and recycling technologies which do not exert environmental loads are strongly demanded [2]. Also, in the developing intelligent materials or smart structures, we must keep firmly in mind the viewpoint of environmental harmony and recycling [3].

Research and development is currently being conducted on intelligent materials or smart structures which themselves recognize the environment, respond to external stimulation and repair automatically, and various concepts have been proposed [4]. Since materials of this kind must involve elements (optical fiber, carbon fiber, shape memory alloy, etc.) systematically to function as sensors, actuators, effectors or processors, they are inevitably composite materials or composite structures [5].

Fiber reinforced thermoplastic (FRTP) is a candidate composite material which responds to multiple requirements such as processing, intelligent and recycling properties [6].

In this paper, the concept of processing of composite materials and structures which are resource and energy saving and are environmentally conscious is described and the possibility of realizing smart properties and recyclability (products reduce into raw materials after their useful lives) is mentioned. Some experiments on recycling of FRTP are also described in the latter part, because the authors think that 'proposal of concept' and 'grasp of existing materials' are both facets of the problem.

2. NECESSITY FOR INTRODUCING ENVIRONMENTAL CONSCIOUSNESS TO FRP INDUSTRY

As mentioned in the Introduction, the preservation of our earthly environment is now an urgent problem. To ensure continuous development of human life, it is necessary to reconstruct the industrial framework which has treated clean water, seas, the atmosphere and resources as inexhaustible. Figure 1 [7] shows a new concept of material development in which environmental harmonization (rooting out pollution) and avoidance of future social costs are important additions to advances in high performance and functionality because of the finite character of Nature.

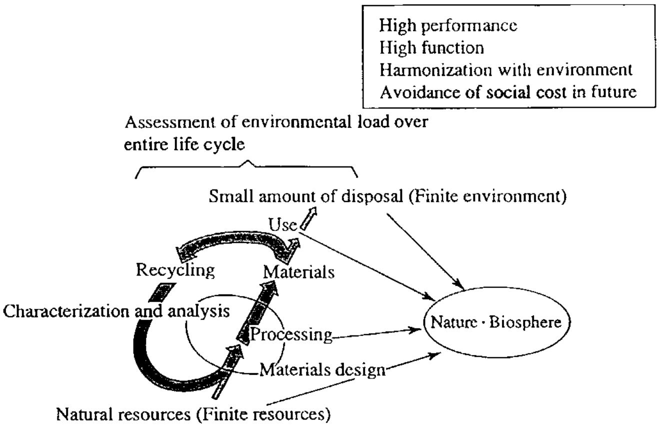

Figure 1. New concept of materials development [7].

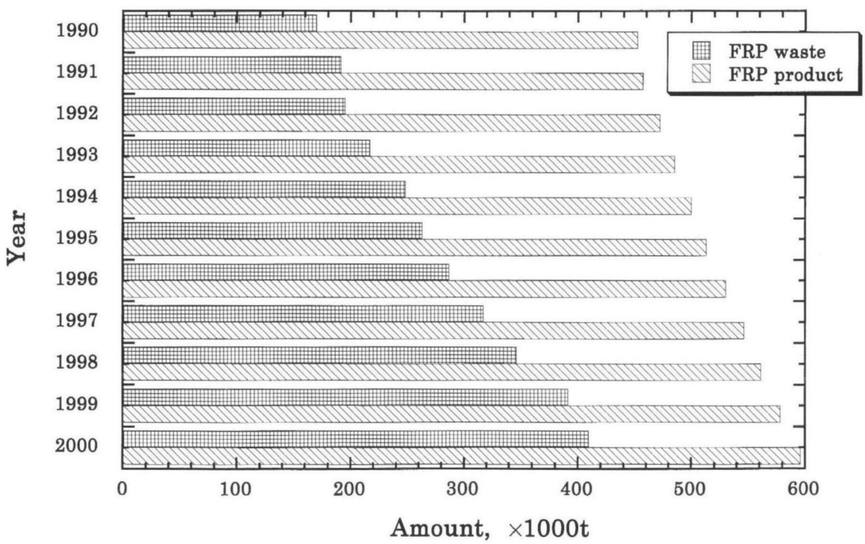

Figure 2. Amount of FRP waste and product.

Figure 2 shows the change and forecast of the amount of FRP production and waste. Both have increased yearly. In 1992, production reached 480 thousand tons, and waste 200 thousand. Sixty percent of the waste comes from three fields: bathtubs, boats and ships, and tanks. The existence of this situation and the intensification of legal regulation of the environment make it necessary to reduce FRP waste, and general waste as well [8].

At present in Japan, almost all FRP wastes are disposed of by reclamation or incineration. However, from the viewpoint of environmental preservation, technical development of uses of combustion heat, chemical recycling which reuses oil and filler components separated by thermal decomposition, and material recycling which produces other FRP products, is required. To ensure continued FRP industry prosperity, it is necessary to regard FRP as the main material of environmentally conscious products [9].

3. MOLDING CONCEPT OF ENVIRONMENTALLY CONSCIOUS FRTP

3.1. Bionic design

The percentage of products produced by molding techniques is very large, since such products are used to ensure safety and reliability of structures made from composite materials. In the case of large structures in the countryside far from urban communities, a large number of structural parts is generally molded in a factory, transported and assembled at the site by a number of persons. This gives rise to mass consumption of resources and energy, causing environmental loss, and inhibits preservation of our earthly environment.

Animals and plants in Nature behave rather differently. For example, trees growing on a steep slope and always exposed to wind blowing in a fixed direction adopt suitable shapes in which annual rings are not concentric circles but eccentric. The bamboo stem diameter hardly varies from ground to top (10 m), and length between nodes varies with height, making a rational shape for a long vertical pole. Silkworms make a scaffold by spitting yarn from three basic planes to build cocoons. Spiders build geometrically excellent cobwebs skillfully utilizing gravity and wind.

The behavior of animals and plants is thus harmonized rationally with Nature and does not present elements which impose loads on the environment. If a molding technique for constructing composite structures at the site is developed by simulating the actions of silkworms, spiders, etc., manufacture of ecologically smart (eco-smart) structures may be possible.

3.2. Cybernetic molder

Figure 3 shows photographs of a silkworm making a cocoon in a box enclosed by four planes [10]. After first making a basic scaffold, the silkworm builds left

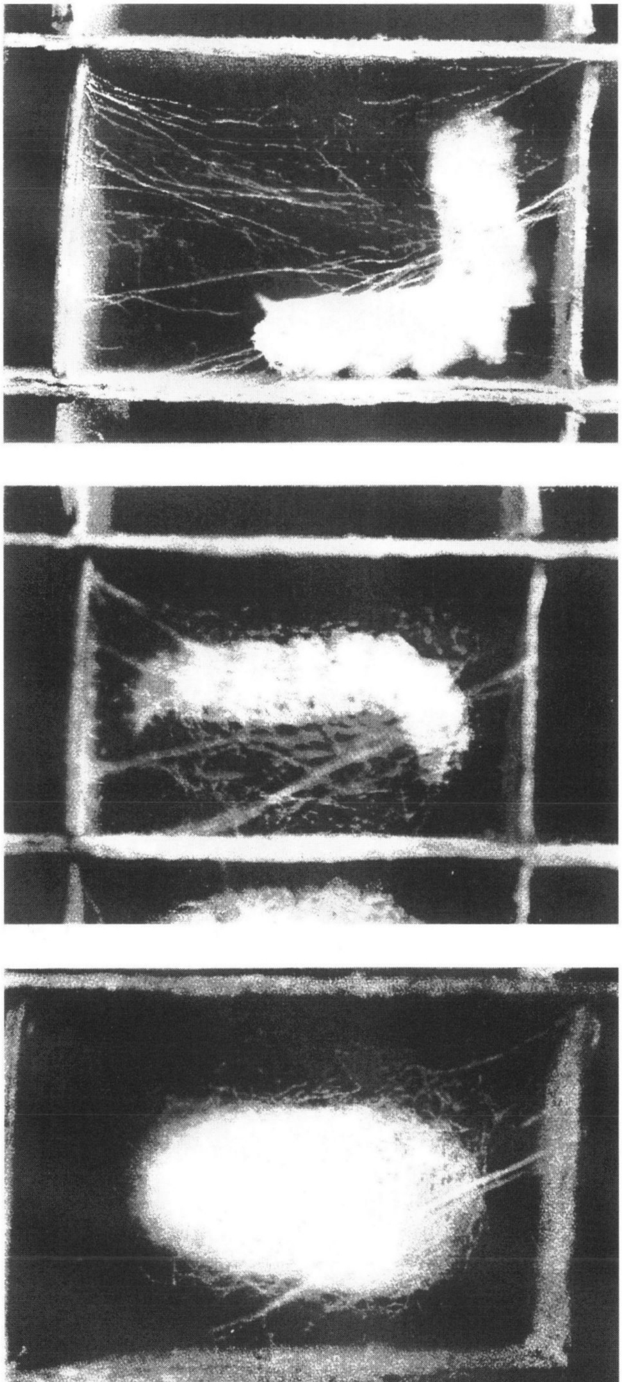

Figure 3. Silkworm making a cocoon.

and right walls moving its head by tracing a figure '8' pattern. This action of the silkworm's head when making a cocoon was simulated by computer. A robot arm controlled in seven axes can perform the same action as the head of a silkworm. Figure 4 shows a flexible robot arm developed by Wada and Shimojo [11], which can simulate the action of a human arm by means of 7-axes control.

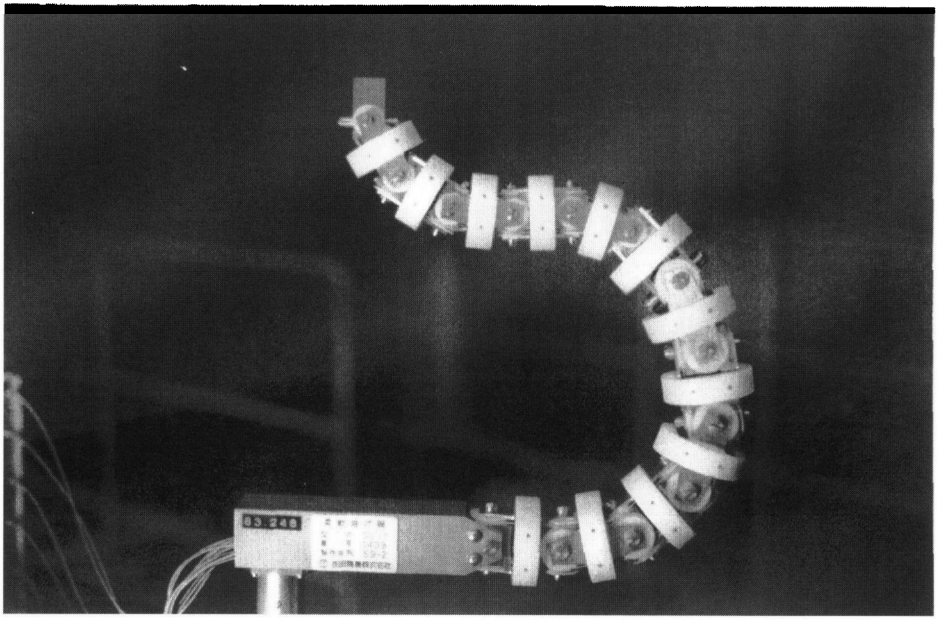

Figure 4. Flexible robot arm.

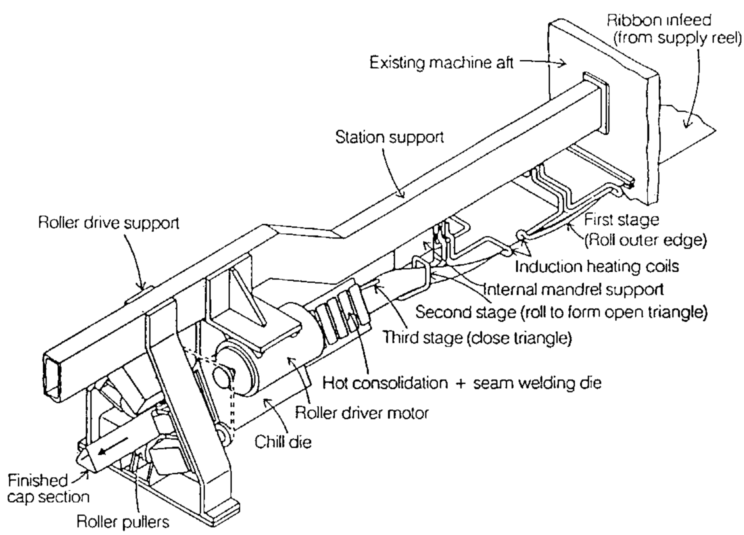

Figure 5. Modified thermoplastic pultrusion molding machine.

In contrast, structural members such as I-type and box-type beams and channel of composite materials are molded continuously by pultrusion. Thus, installing the molding machine shown in Fig. 5 on the tip of the flexible robot arm which acts like the silkworm shown in Fig. 4, produces a cybernetic molder.

3.3. Environmentally conscious composite structures

Figure 6 shows molding of a concrete FRTP composite structure using the cybernetic molder. This machine has two molding arms. One forms the exterior structural frame spirally; the other molds the wavelike web synchronously, and builds a super-sized dome *in situ*. To improve safety and reliability of such super-sized structures and to achieve maintenance-free usage, the intelligence of the composite material itself and smart properties of the structure as a whole become important. This molding method is also very advantageous for embedding functional elements

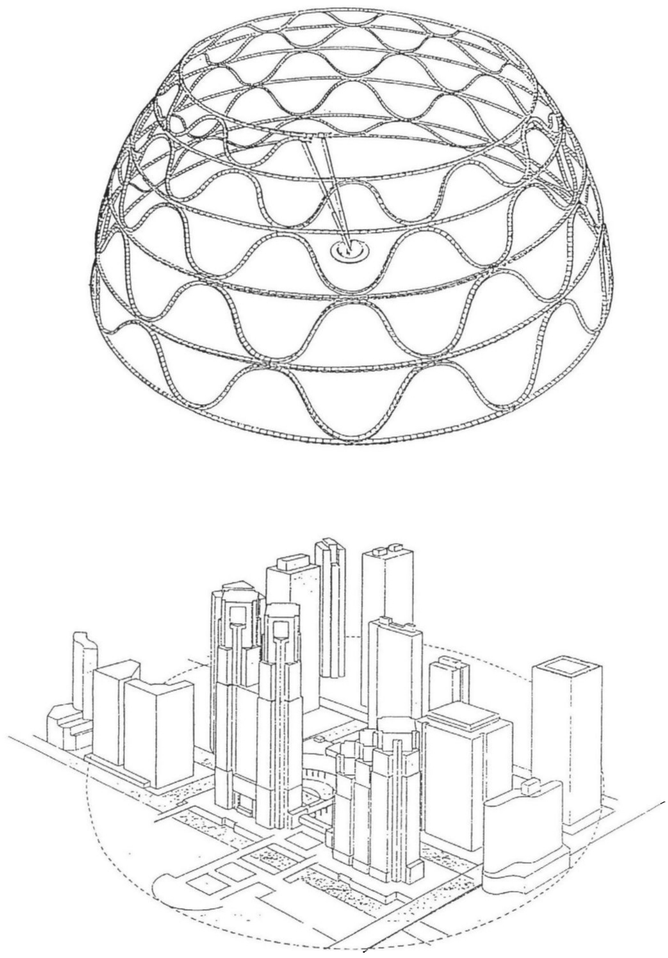

Figure 6. Concept of *in situ* composite structure.

such as sensors of fiber-type. However, if the material of the super-sized structure cannot by recycled when its role is over or it is rebuilt, but is simply converted to a large amount of waste that degrades the environment, it cannot be called eco-smart or a representative of material revolution.

When a spider dangling from a branch is surprised, it runs away, drawing and recovering yarn into its body to reuse next time. This is an ideal mode of recycling. In the material recycling of FRTP, it may be possible to reduce FRTP to reinforcing fiber and matrix resin by heating and drawing as spiders do. In the following, a closed-loop material recycling process is examined as a more general scheme of FRTP recycling.

4. CONCEPT OF FRTP ECO-SMART COMPOSITE STRUCTURE

4.1. Endowment of intelligence and recyclability

The upper part of Fig. 7 shows a schema of smart composite structures used for aircraft, super-sized structures or their members. As is seen from this figure, layers exist in which intelligent functions such as sensors, actuators or effectors are included systematically. These layers detect and visualize microscopic cracks when they occur, invoke repairing action, suppress propagation of cracks and prevent final fracture of the structure. Thus, these layers ensure the safety, reliability and maintenance-free properties during the usage of the structure. Research conducted to date suggests that optical fiber, carbon fiber or shape memory alloy etc. should be embedded in the intelligent function layer.

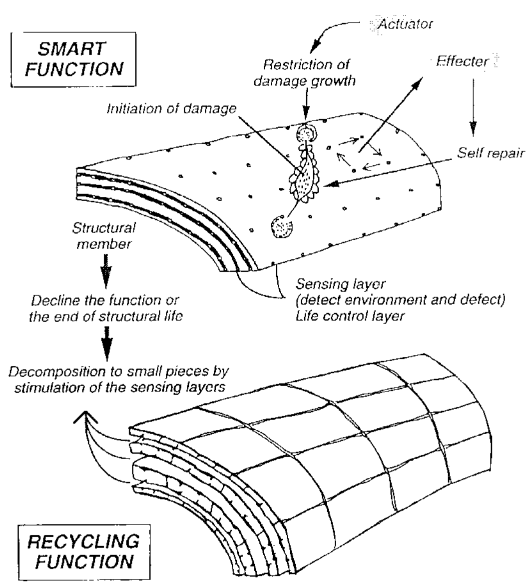

Figure 7. Schematic illustration of smart composite structure.

Furthermore, as a structure's functions decline, the intelligent function layers act as self-decomposing layers to reduce the structures to small pieces which can be easily recycled, as shown in the lower part of Fig. 7. In breaking for recycling, some special condition must be used which can never occur during practical use, such as an intense radiation of microwave. So strength in practical use and easy breaking properties for recycling are not inconsistent. We will call composite structures which possess intelligent functions and which are easily recycled when their lives are over without imposing earthly environmental loads, eco-smart composite structures.

4.2. A breakthrough idea

A structure using carbon fiber reinforced thermoplastics including optical fiber (OF-CFRTP) is a candidate as an environmentally conscious smart composite structure. When an external force acts on such a structure and it develops microcracks, the embedded optical fiber (OF) is elongated at that portion. This causes a point of high stress concentration which is detected as phase deviation of light passing through the OF. If it is possible to locally heat and soften the matrix resin at that portion based on the above information, the carbon fibers contract (linear thermal expansion coefficient is negative) and act as a press to repair the microcracks (see Fig. 8). The strain at which microcracks develop in CFRP is said to be about 1% and elastic limit strain of OF is 3%. So we can detect the sign and deal with it before fatal damage of the matrix occurs.

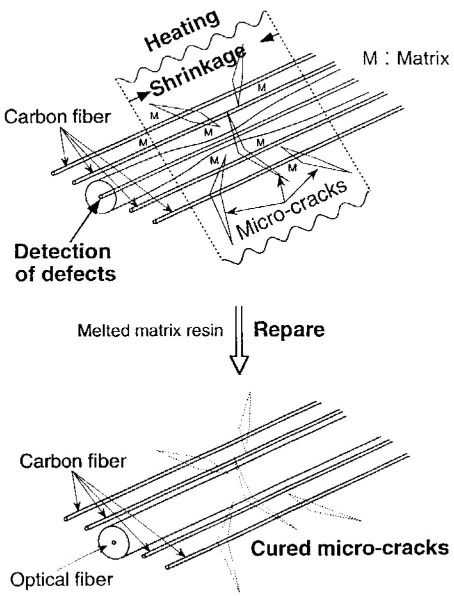

Figure 8. Concept of self-repairing function.

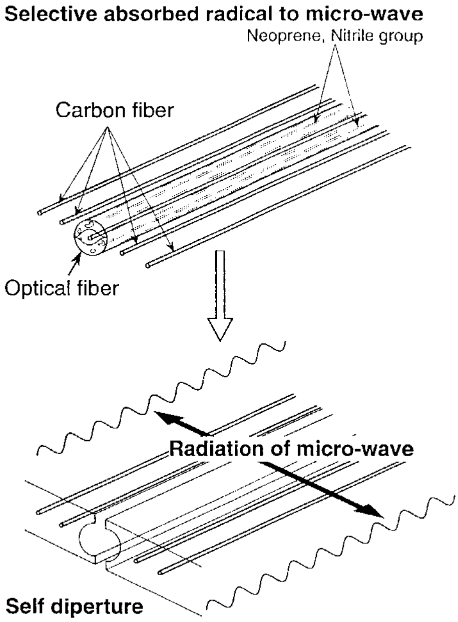

Figure 9. Concept of self-breakdown function.

With regard to the environmentally conscious function, if we add a microwave-absorbing polymeric group such as neoprene or nitrile in the OF covering agent, and expose the material to microwave at the end of its life, the structure itself breaks down into small pieces along the embedded OF. Of course, carbon fibers also absorb microwave simultaneously. But if the intensity of radiation is sufficient, the OF covering agents can absorb and shatter, to be accompanied by heat generation of carbon fiber. This will simplify recycling when the product life is over or if it is rebuilt (see Fig. 9).

5. POSSIBILITY OF FRTP CLOSED-LOOP RECYCLING [12–14]

5.1. Concept of closed-loop recycling of FRTP

As shown in Fig. 10, continuous fiber FRTP products are used for strength members bearing external forces. Long or short fibers are used where less strength is needed, such as bumpers of automobiles and helmets, and dispersing particles are used for enclosures of TV, radio sets, etc. Regarding each utilization mode (continuous, long or short fiber, and particle dispersion) as one step in the FRTP life cycle (5 to 20 years), separating resin components and residue (filler) by means of dry distillation and reusing them as raw materials of FRTP again would complete the closed-loop material recycling of composite materials.

To examine the material recycling of FRTP, it is necessary to conduct the following research:

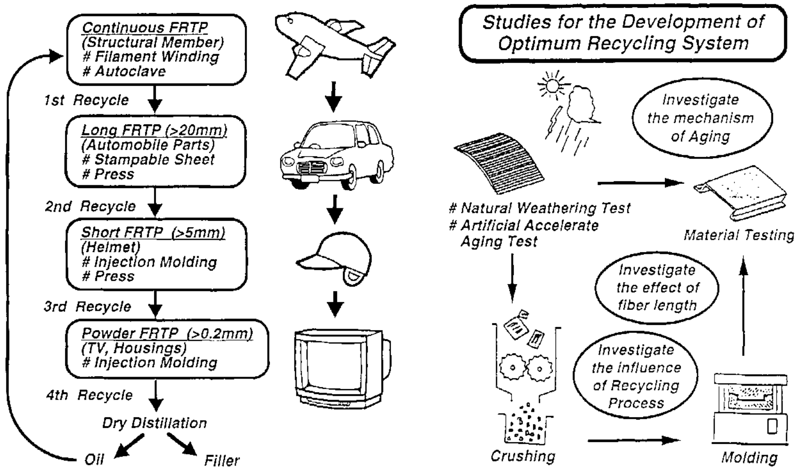

Figure 10. Concept of closed-loop material recycling for FRTP.

(1) Clarify fiber length dependence on the reinforcing mechanism.

(2) Develop accelerated exposure technique for FRTP assuming 5- to 20-years cycle and determine strength reduction.

(3) Identify the influence of the thermal history (number of recycling steps) on performance of products.

5.2. Clarifying fiber length dependence on the reinforcing mechanism

The length of reinforcing fiber decreases step-by-step in each recycling stage. In the first recycling from continuous (C) to long (L), in the second from L to short (S) by thermoforming after cutting the respective mother materials, and in the third from S to powder (P) by means of injection molding. An example of strength performance (residual strength) of GFRP is shown in Fig. 11. Strength performances of L-FRTP, S-FRTP and P-FRTP are 57, 38 and 66%, respectively. Even in the stage of P, reinforcing fibers maintain sufficient aspect ratio (higher than 100), the length of which is about 200 μm. So we consider that the high strength performance of P is due to the high degree of orientation produced by injection. Modulus performances are as high as 70%.

5.3. Weathering durability and accelerated deterioration characteristics of FRTP

Assuming the life as FRTP products to be 5 to 20 years, material deterioration during this period was investigated by conducting natural exposure tests and accelerated exposure tests using an intense xenon lamp weather meter, and acceleration and correlation were examined. Figure 12 shows some of the results. It can be seen from this figure that strength decreases 20% during the initial half year but is stable thereafter and modulus remains at about 90% of its pre-exposure level. The results of accelerated exposure testing on the amounts of ultraviolet radiation and water

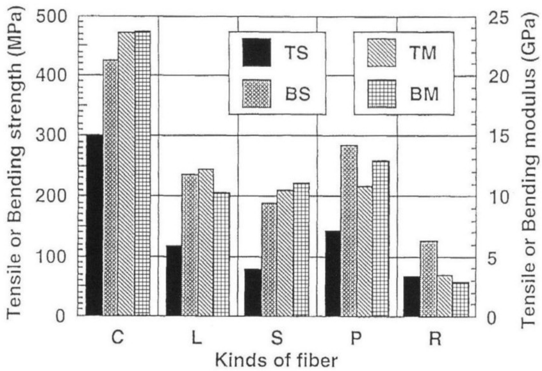

Figure 11. Change of tensile and bending properties in GF-FRTP laminates with various fiber lengths:

Symbol	C	L	S	P	R
Meaning	Continuous	Long	Short	Powder	Resin
V_f	46%	31%	31%	28%	0% .

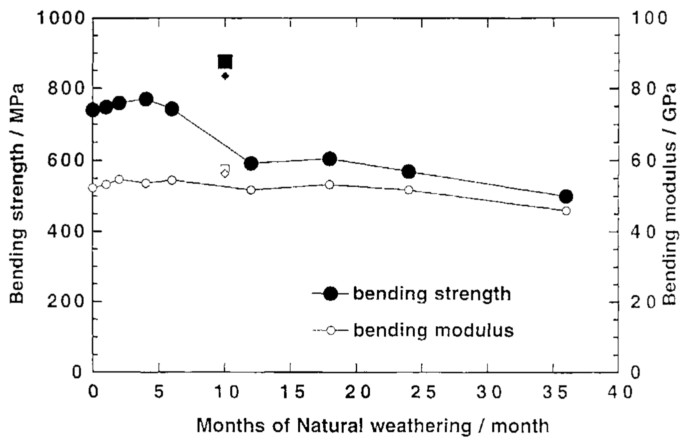

Figure 12. Deterioration of FRTP by natural and accelerated exposure tests. Bending strength (■) (□) and modulus (◆) (◇) after accelerated exposure treatment corresponding to 10 (■) (◆) and 15 (□) (◇) years.

spray corresponding to 15 years are also shown in the figure. There is no strength reduction and the correlation between natural and accelerated exposure tests is low.

5.4. Effect of thermal history from repeated material recycling

Reused FRTP is subjected to repeated crushing and thermal exposure. Some results of testing these influences are shown in Fig. 13. In this figure, R and V represent recycled and virgin materials. From this figure, it is seen that R materials obtained from first and second recycling processes have less bending strength than each reference, meaning that thermal cycling tends to reduce strength. However, for

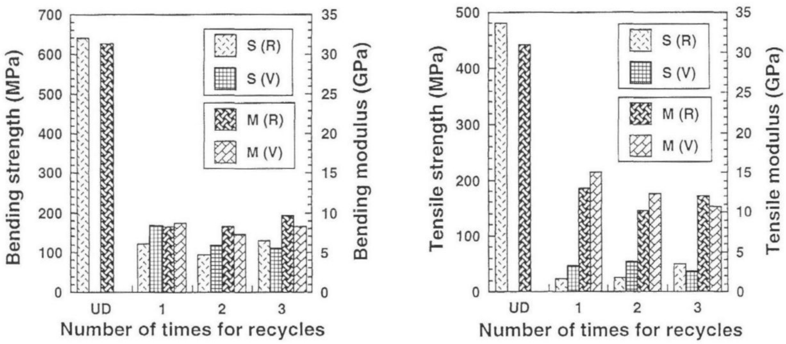

Figure 13. Change of bending and tensile properties in GF/PP laminates due to thermal history by number of recyclings.

the third R material, both the strength and modulus are higher than those of the reference. We interpret this to mean that bundles of fiber have been thoroughly broken to pieces by repeated recycling and the reinforcing effect is improved. The bending modulus is almost independent of the fiber length and the number of recyclings, and is about 1/4 of that of the unidirectionally reinforced composite.

6. CONCLUSIONS

Materials requirements will become increasingly higher and more diversified, and greater functionality will be expected in addition to safety and reliability. Intelligent materials or smart structures are practical concepts and are becoming the ultimate objectives of research on materials and structures. At the same time, preserving our earthly environment is now an urgent problem threatening the survival of the human race. When producing materials and structures, it is therefore important not to impose loads on the environment. In this report, application of bionic design and the possibility of intelligent properties and material recycling in the molding process have been described, paying attention to fiber-reinforced thermoplastic composite material, a representative candidate of polymeric intelligent materials. Although the new materials are now only in the conceptual stage, in the present age materials transition from the conceptual stage to practical technology will proceed much more quickly than before.

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