RECENT PROGRESS IN EXPERIMENTAL AND COMPUTATIONAL MECHANICS APPROACH TO PERFORMANCE ASSESSMENT OF COMPOSITE MATERIAL STRUCTURES

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SUMMARY: The essential difficulties to assess the performance of composite material structures lies in the fact that various kinds of mechanical, geometrical and material inhomogeneity should be taken into consideration in every phase of analysis, ranging from fiber/matrix interfaces to adhesive joints of structural components. However the recent advances in experimental and computational mechanics have been making it possible to offer more flexible and versatile techniques, ranging from micro (or meso)-mechanics to macro-mechanics, for more realistic and accurate modeling of composite material structures, not only for structural performance but also for damage growth process. Several typical and successful applications of these approaches are illustrated and discussed with special reference to characterization of damage and damage progression including some emerging new fields such as health monitoring techniques of composite material structures.

KEYWORDS : Experimental and Computational Mechanics, Micro(Meso)-Mechanics, Macro-Mechanics, Modeling, Damage, CAI, Damage Tolerance Design, Health Monitoring.

INTRODUCTION

As practical applications of advanced composite materials are increasing in number and scale, accurate and proper models for performance assessment of composite material structures are becoming more and more important. As the major characteristics of composite material structures are "materials inhomogeneity and anisotropy", "integration of materials and structures" and "indivisibility of materials and structural design", the "performance" could be fully realized as a result of synthetic "materials and structural system" technology based on integration and fusion of multi-functionality or some possible "smart" functionality as shown schematically in Fig. 1. The approach of "micro (meso)"-mechanics or "macro"-mechanics can be flexibly and properly used depending on the viewpoint of modeling, which does not necessarily depend on its physical scale. Furthermore, the recent advances in experimental and computational mechanics have been making it easier to propose a more realistic and accurate damage modeling and to estimate a complicated failure process of composite materials if the both approaches are properly combined and fused.

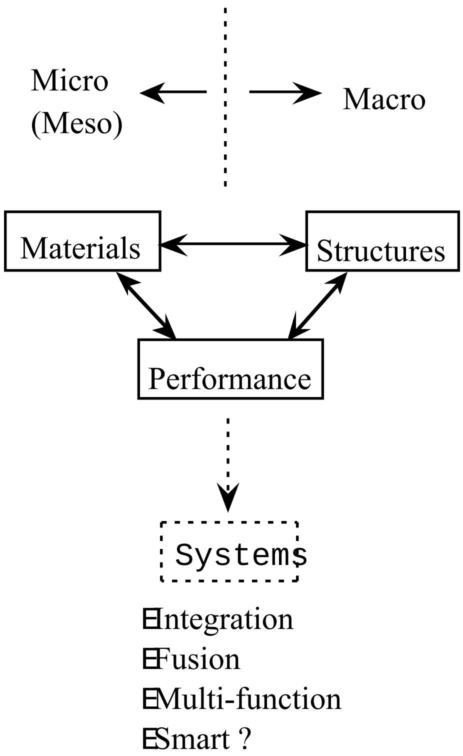


Fig. 1: Integration and fusion in "materials and structures" systems technology.

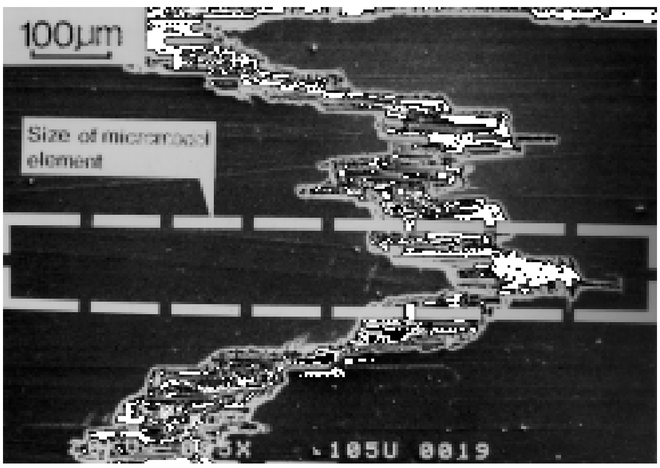
The ranger of matrix of composite materials has now been expanded from polymer (PMC), metal (MMC) to ceramics (CMC). As the strength properties are essentially varied among PMC, MMC and CMC, the basic aspects of applied experimental and computational mechanics appears to be common. Such recent trends are overviewed by referring to the recent achievements in PMC as structural materials in this paper. The author does not intend to make a comprehensive literature survey, but to introduce and discuss some typical trends in approaches and modeling of composite material structures by referring to the author's own experiences as typical examples of general and common nature.

DAMAGE OF COMPOSITE MATERIAL STRUCTURES

The micro (or meso)-mechanics and macro-mechanics have relatively clearly divided roles in mechanical characterization and materials design of PMC in comparison to MMC and CMC since PMC is generally used in laminated structures. For examples, delamination failure of PMC has recently been extensively studied in relation to interlaminar fracture toughness from macroscopic viewpoint. Especially many studies have recently been aimed at characterization of compression after impact (CAI) strength of CFRP since it is very important in improving the damage tolerance of CFRP laminates applied to primary structure of airplanes. It has recently been revealed that the macroscopic nature of delamination is closely related to the microscopic interfacial strength. Advanced experimental methods have recently successfully applied to detect and visualize the initiation and growth of transverse cracks and delamination in CFRP cross-ply laminates. Novel micro-mechanical models were proposed to explain the experimental results. It is very important to make a direct and precise measurement of interfacial mechanical properties in order to establish "interfacial mechanics" from a view-point of micro- mechanics. For this reason, more and more attention has been directed towards bridging between microscopic and macroscopic aspects of interfacial strength. As there has still been a big gap between characterization of damage behaviors of laminae, laminates and laminated composite structures, an useful design methodology is expected to fill the gap towards the real damage tolerance design.

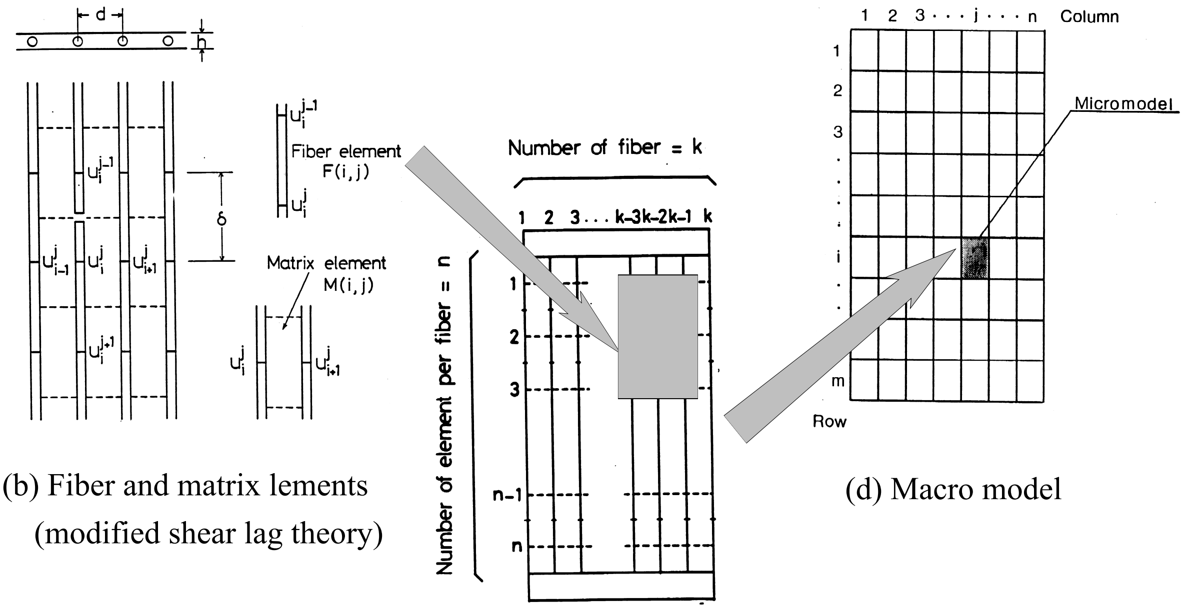
Basic Failure Models

The failure process of composite materials is a very complicated accumulation process of damage due to random failures of fibers, matrix and interfaces, leading to a complicated zigzag cleavage plane of a specimen. A Monte Carlo simulation is one of the most effective methods to analyze the statistical nature of such a complicated stochastic phenomenon as a failure process of composites and many studies have so far been carried out. A simple failure model, referred to "Rosen-Zweben model" , has often been applied, in which only random fiber breaks and stress concentration in the nearest fiber to the broken one are taken into account. This simple model leads to a flat cleavage plane of a specimen, apparently different from a typically observed one as shown in Fig. 2(a). Figure 2 (b) shows a new failure simulation model of unidirectional lamina considering the effect of matrix shear failure as well as fiber breaks based on a shear-lag theory, in which a failure can occur randomly not only in fiber elements but also in matrix elements [1]. This micro model (Fig. 2(c)) was successfully applied in simulating a static and dynamic failure process leading to such a complicated pattern as shown in Fig. 2(a). A macro model composed of elements of such micro models was also proposed as shown in Fig. 2(d), which was effectively used in estimating the statistical nature of strength properties of unidirectional lamina specimens of actual size [1].



(a) Observed tensile failure pattern of unidirectional CFRP

Fig. 2: Stochastic tensile strength simulations based on shear lag model.



(b) Fiber and matrix lements
(modified shear lag theory)

(c) Micro model
(k=11, n=15)

(d) Macro model

Fig. 2: Stochastic tensile strength simulations based on modified shear lag model.

It is one of the most important points in materials design to increase the fracture energy leading to a zigzag failure pattern based on a suitable control of interfacial adhesion and stress conditions. Some micro-mechanical model is required in order to characterize such an experimental behavior as shown in Fig.3. For this purpose, a finite element model was formulated as shown in Fig. 4, in which each element is connected by normal and shear springs between adjoining nodes [2]. The failure process is simulated by breaking spring elements one by applying the failure criterion to spring stresses based on an increment scheme. The effect of interfacial strength on the tensile failure process of high modulus pitch-based CFRP was simulated by using a single fiber embedded specimen and an unidirectional strand specimen based on this model. A dynamic FEM simulation was performed on an unidirectional strand specimen, which showed that the lower interfacial strength gave a higher tensile strength leading to the simulated results similar to the observed failure modes as shown in Fig. 5 [2].

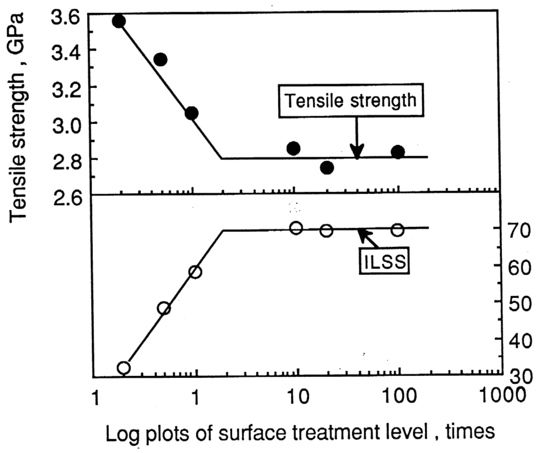


Fig. 3: ILSS and tensile strength due to surface treatment levels.

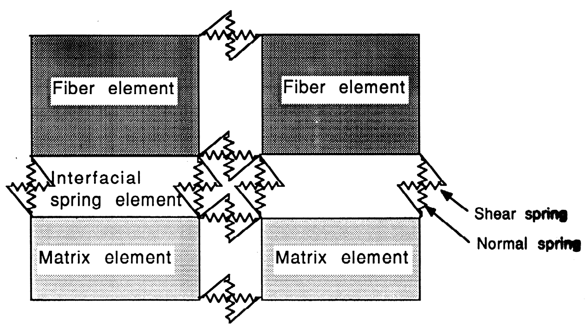


Fig. 4: Dynamic FEM simulation model with inerfacial spring elements.

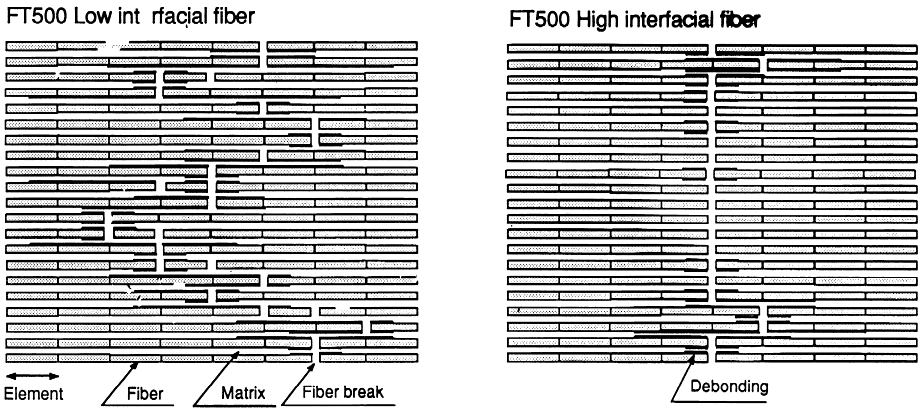


Fig. 5: Observed and simulated fracture surfaces due to different surface treatment levels.

CAI Strength Model

Delamination is one of the most important life-limiting failure modes in laminated composite structures. Low speed impact, for example, introduces delamination into a composite laminate, and remarkable reduction in compressive strength is commonly observed. Compression after impact (CAI) strength is considered as one of the most important design limits in aircraft structures. The resistance of delamination growth is well measured n terms of the interlaminar fracture toughness. Many test methods have been proposed for the pure mode, I, II and III loading and mixed mode loading. Recent research reports suggested the importance of the mode II fracture toughness for composite structures because interlaminar shear is the most common loading condition for delaminated composite structures.

The recent advances in experimental and computational mechanics has made it easier to propose a more realistic and accurate damage modeling and to simulate a complicated failure process of composite materials if the both approaches are properly combined and fused as shown schematically in Fig. 6 [3]. Such an approach is sometimes referred to the so-called "hybrid" experimental/computational mechanics. Figure 7 shows an example of such approaches to make a non-destructive evaluation of the CAI strength. Vibration pattern imaging and FEM were applied to characterize the dynamic response of the impact-damaged specimen. A new finite element model was proposed for the impact-damaged region in which the stiffness reduction was expressed as equivalent thickness degradation as shown in Fig. 7. The model was applied to buckling analysis of the damaged specimen, which gave a good estimation of the CAI strength [4].

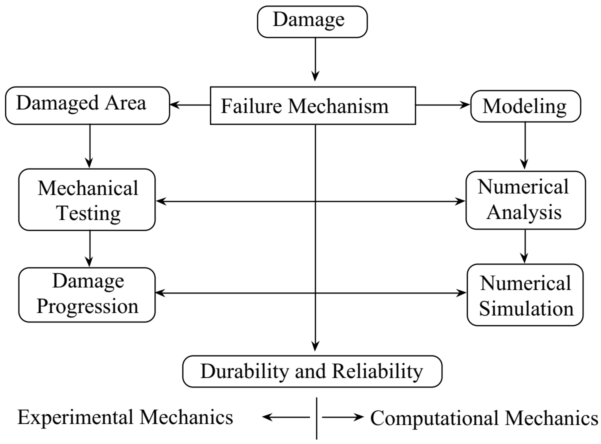
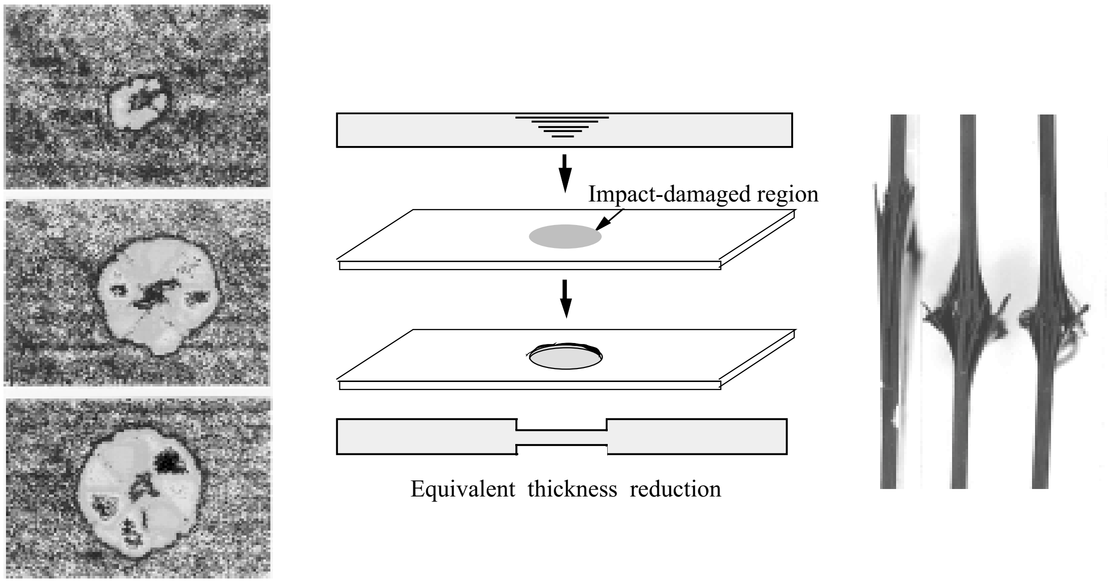


Fig. 6: Fusion of experimental and computational mechanics to evaluate damage progression.



Observed damage ¤ Model ' Observed failure mechanism

Fig. 7: Equivalent thickness concept applied to a cross section in an impact-damaged region.

Interlayer Toughened CFRP

Among various candidates for toughening graphite/epoxy laminates, the concept of "interlayer" appears to be most promising. Interlayer refers to a mixture of thermoplastic particles and thermoset base resin, selectively localized between laminae as a thin resin film, as shown in Fig. 8 and 9. A newly developed interlayer toughened graphite/epoxy laminates (T800H/3900-2) has demonstrated excellent compression after impact (CAI) strength and hot-wet characteristics.

The toughening mechanism of interlayer was first characterized in terms of static mode I and II interlaminar fracture toughness in conjunction with fracture mode transition. It was shown that the improvement in toughness was greater in mode II than in mode I, mainly due to fracture region transition in mode I, which is deflection of crack path from interlayer to intralaminar [5]. Then the mode II fatigue delamination growth behavior of the interlayer toughened graphite/epoxy laminates was comparatively evaluated together with the other type of graphite/toughened epoxy laminates and conventional untoughened graphite/epoxy laminates by a precise fatigue test system. The results showed that the two kinds of toughened laminates exhibited a relatively higher resistance to mode II delamination growth at the high delamination growth rate than the conventional laminates, but that they had no effect on improving the toughness in terms of the threshold mode II energy release rate [5].

An elasto-plastic analysis of a crack in an inhomogeneous interlayer containing particles was also conducted based on two-dimensional finite element modeling assuming that particle was more compliant than matrix. Figure 10 shows a mode II stress and strain distributions around the particles [6]. Several toughening mechanisms by interlayer were discussed on the basis of the stress distribution near a crack tip in terms of plastic region and crack propagation path.

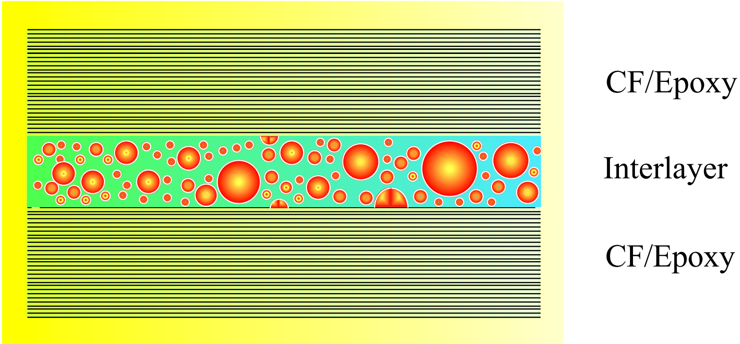
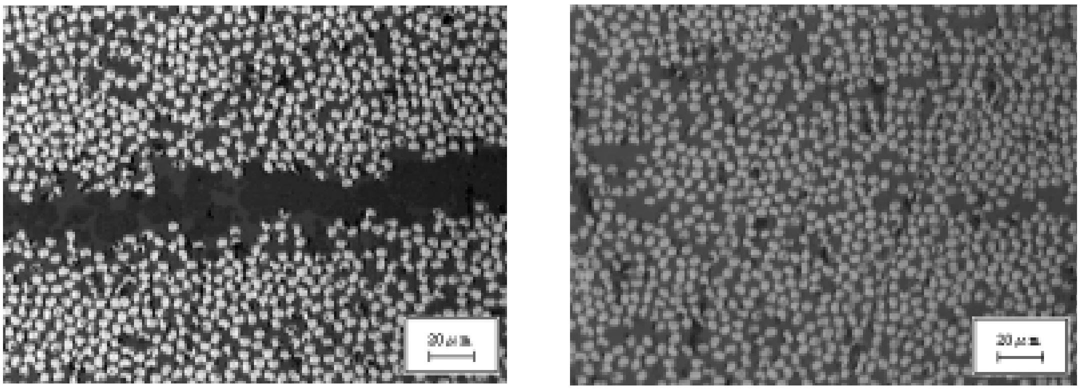


Fig. 8: Concept of thermoplastic particulate interlayer toughening technology.



(a) T800H/#3900-2 with toughened interlayer (b) T800H/#3631 without interlayer

Fig. 9: SEM observations of cross sections of unidirectional CFRP.

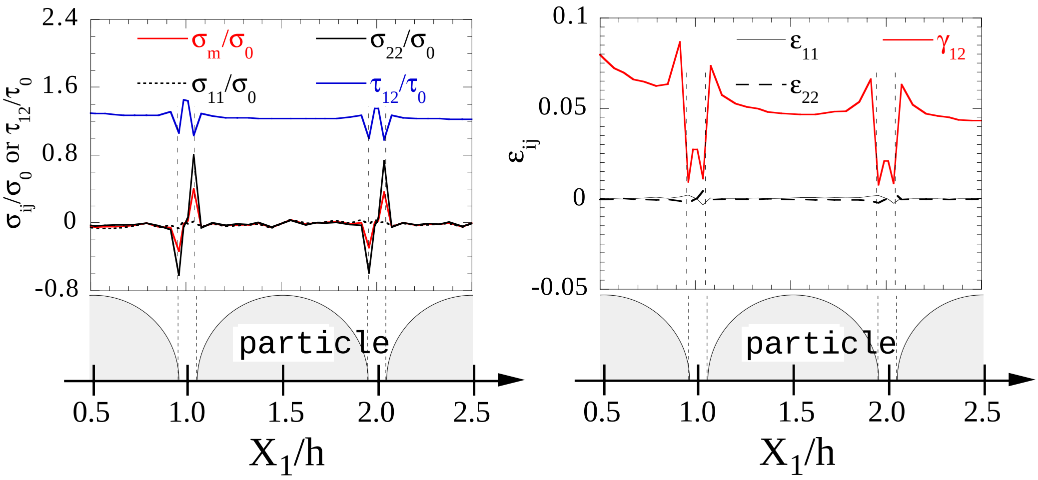


Fig.10: Elasto-plastic stress and strain distributions around particles under mode II.

MODELING OF COMPOSITE MATERIAL STRUCTURES

Laminated composite material structures (composite laminates) possess various kinds of mechanical, geometrical and material inhomogeneity in every phase of analysis, ranging from fiber/matrix interfaces to adhesive joints of structural components, as illustrated in Fig.11. Furthermore, in practical problems, these inhomogeneity should be treated at a time as shown in Table 1. In particular, in structural analysis and design, the inhomogeneity in "Laminate-like Phase" must not be overlooked. Therefore, an accurate and proper numerical model for composite laminates should take their inhomogeneities into consideration efficiently [7].

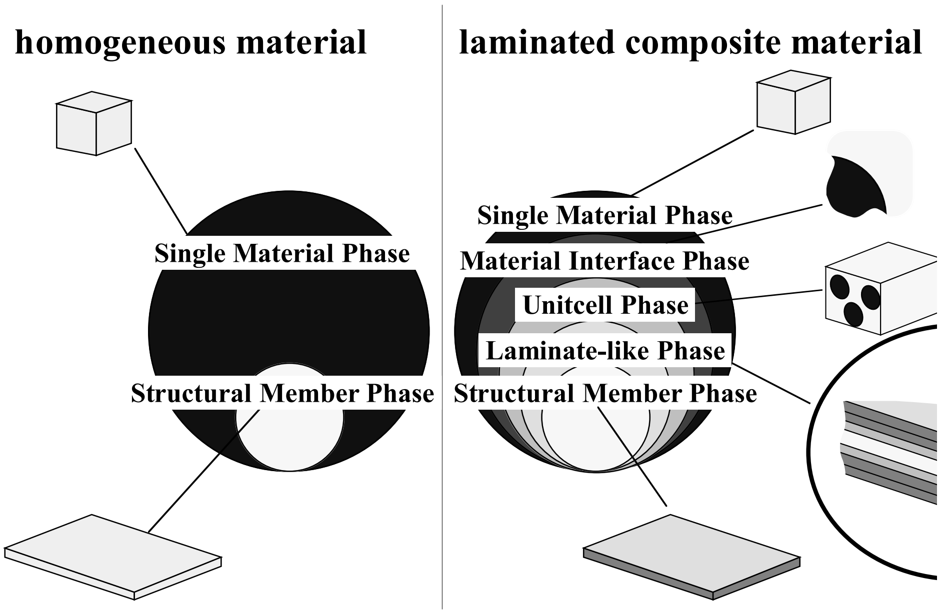


Fig.11 : Schematic comparison of homogeneous materials and composite materials.

Table 1: Combinations of different inhomogeneity levels and examples in composite laminates.

inhomogenity levels			examples
structural member level	+	single menber level interface level pointwise level	mesomechanics micro/macro analysis based on homogenization method
structural member level	+	layerwise level	delaminated member CAI
layerwise level	+	single member level interface level pointwise level	failure mode of sandwich menber interlaminar properties toughened interlayer
structural member level layerwise level	+ +	single member level interface level pointwise level	free-edge effect laminated member with embedded film component adhesive joint with overlays

Structural Analysis of Monocoque Sandwich Boat Hulls

The six years program was carried out in 1990 - 1995 to develop the prototype of new light-weight racing boats with the use of advanced composite materials for the purpose of creating more exciting race. The conventional racing boats made of plywood are about 3 m in length, have a maximum speed of about 80 km/h, and are equipped with a 30-PS outboard engine. The conventional wooden boat structure was redesigned and manufactured into seven types of prototype models: from hybrid FRP sandwich construction with seven frames and four longitudinals and finally into CFRP monocoque sandwich construction without frame and longitudinal. Figure 12 shows a finite element modeling of boat hull : 8-node thick shell elements for the upper and lower skin faces and 20-node 3-D continuum brick elements for the core layer. Such a hybrid modeling of sandwich constructions is generally very cumbersome and time consuming for structural design purpose. As the maximum weight reduction was achieved as much as 44.1 %, the bottom shell of two types of CFRP monocoque sandwich boats were broken under endurance test as shown in Fig.13. For this reason, the monocoque sandwich design was reexamined and the bottom shell was reinforced based on a detailed finite element analysis under the assumed slamming load as illustrated in Fig.14 [8].

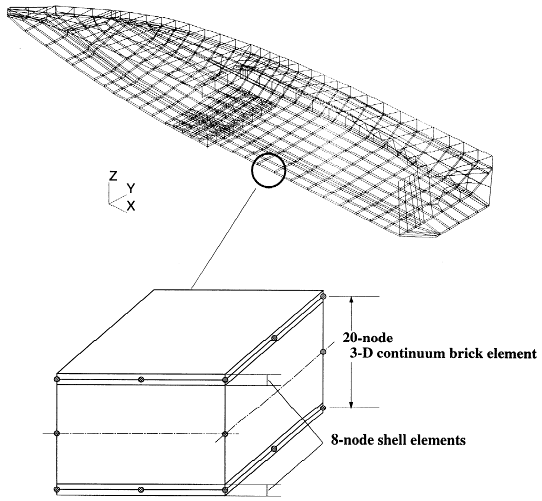


Fig. 12 : Finite element model for monocoque CFRP / foam core sandwich boat hull.

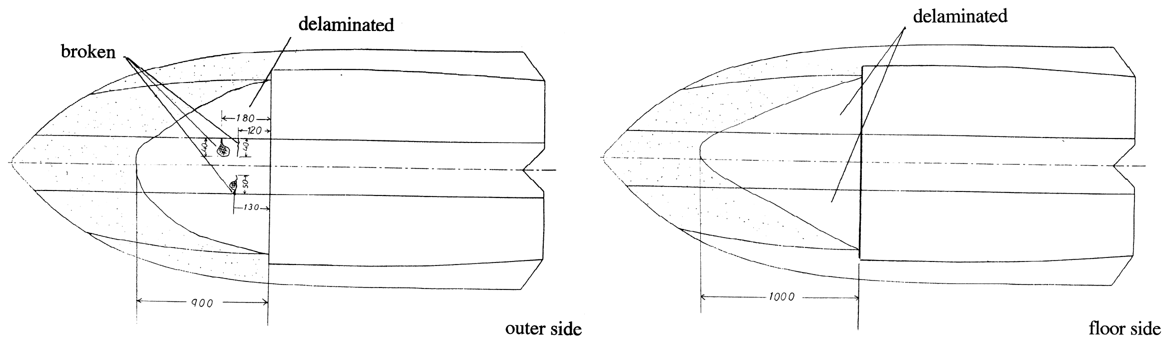
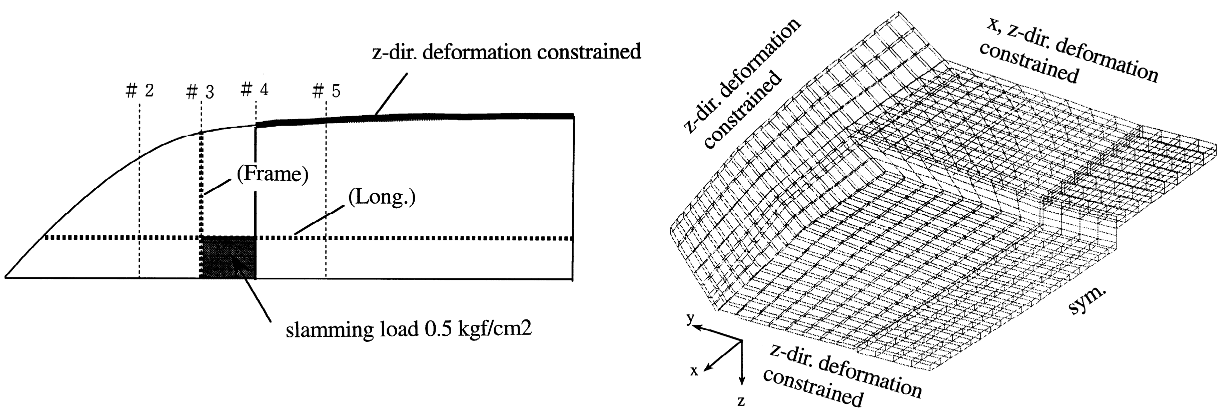


Fig.13: Failure modes in bottom shell around step of racing boat.



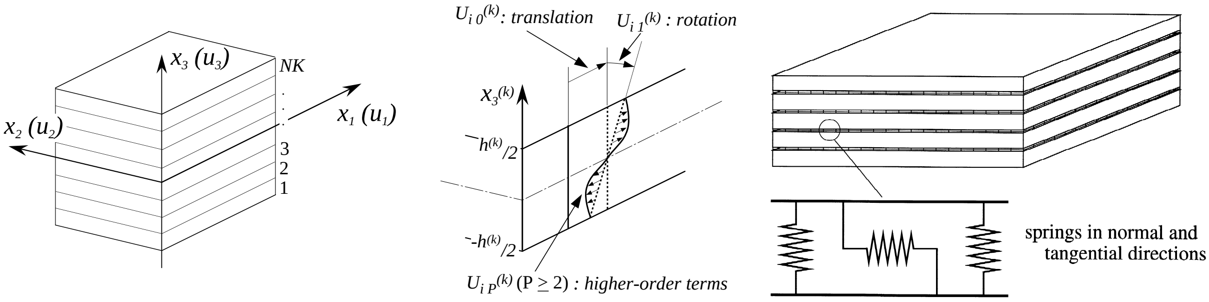
(a) Modeling of slamming load

(b) Finite element meshes for bottom shell around step

Fig.14: Finite element analysis of local stress and strain in a bottom shell due to slamming.

Hierarchical Layerwise Higher-Order Finite Elements

As there is a general remark that any structural problem can be solved by single-layer plate/shell elements and/or 2-D, 3-D continuum solid elements in finite element (FE) numerical analysis, this approach can not give a flexible nad versatile analysis tool for laminated composite structures. For this purpose, a refined displacement-based layerwise FE is proposed for the stress analysis of N-layered general laminated composites, which is capable of simultaneously predicting global and local stresses as shown in Fig.15. The feature of the proposed FE is based on the polynomial series displacement assumptions for each layer, as shown in Fig.15(b), which leads to the cubic variations of the in-plane strains, the parabolic variations of the transverse shear strains and the linear variation of the transverse normal strains in the thickness direction. The displacement continuity at interlayers are approximated by introducing imaginary springs attached at the interlayers in the normal and tangential directions as shown in Fig.15(c). This scheme is a kind of extended application of the penalty method to displacement constraint problems at the interlayer. The interlaminar stresses can be directly evaluated as the reactions of the springs [7].



(a) Coordinae system (b) Deformation of layer'k' (c) Interlaminar springs

Fig.15 : Layerwise higher-order finite element with penalty method

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Development of CAD/CAM/CAE

The conventional CAD/CAM/CAE systems have been developed mainly for isotropic materials, then, anisotropic laminated materials have been put in an additional position. The conventional modeling takes laminated materials as only material data for each finite element, so that he conventional systems have less flexibility in designing and analyzing composite materials. As laminated materials are made by lay-up process step by step and laminated materials are put together to structures, laminated composite structures should be handled not only as materials but also as stratum structures as shown in Fig. 16. Lamina is composed of fiber and matrix, which means that lamina has thickness, strength and modulus as single-ply plate. Ply means that lamina is defined on tool mold with some area and fiber direction. Laminated structures consists of plies with stacking sequence. After laminated structures are treated as stratum structures in the computer systems, a designer can easily make models of laminated structures according the images. This means that a designer does not need to consider thickness and stacking sequences in each section, because these properties should be automatically assigned during definition of every plies [9].

Figure 17 shows a flowchart of laminate design and process design. The computer aided design and manufacturing systems should have such characteristic points as easy laminate definition , high response to design change, layerwise structural analysis, easy layerwise evaluation and lay-up simulation. After definition of laminates, it is efficient to analyze structures by means of FE methods. Since finite element meshes belong to the laminated structure model, design change requires regeneration of meshes. In the view point of design spiral, it is desirable to generate finite element meshes automatically. In a laminate, as the properties of layers are very different each other, then it is necessary to analyze layerwisely. And it is also required to display and evaluate stresses about each layer. That is to say, a layerwise postprocessor system is required. It is made possible to display same layer extend over different stack sequences, in spite of discrepancy in layer numbers, in the developed system, as shown in Fig.18 [9].

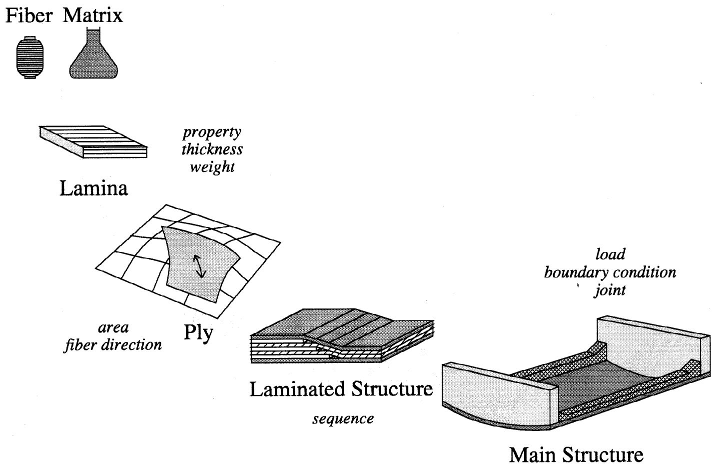


Fig.16: Stratum of laminated composite structures.

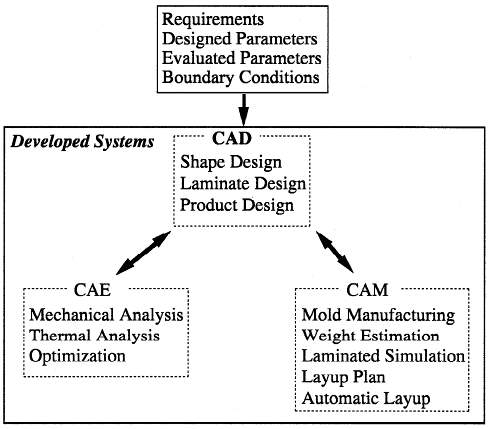


Fig.17: Flowchart of lamination and process design for composite structures.

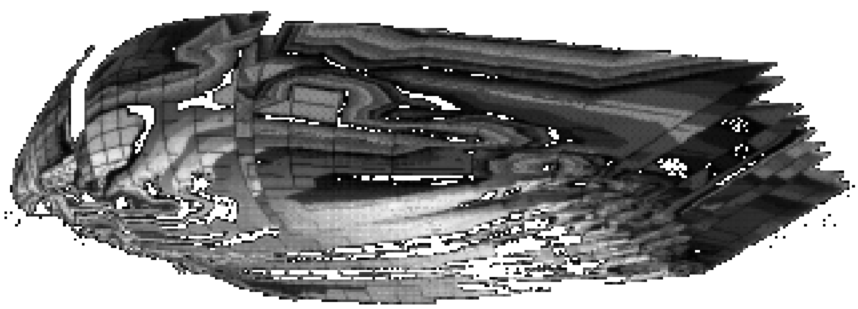
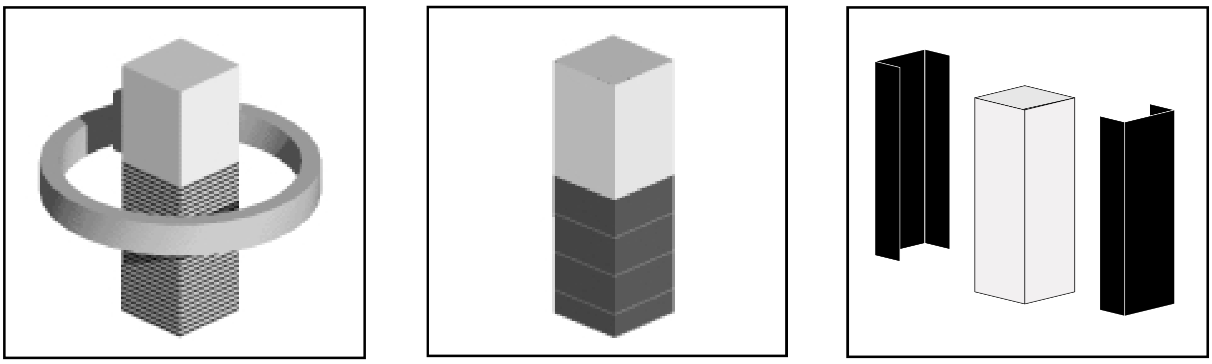


Fig.18: Layer-to-layer stress distribution contours of IOR yacht hull.

Reinforcement of Infrastructures with Composite Wraps

Much attention has recently been paid to rehabilitation such as repair and preservation of infrastructure with the use of fiber reinforced plastics (FRP) wraps or sheets, as shown in Fig.19. A widespread use of carbon fiber sheets has already been found in Japan with hundreds of field applications including repairs of bridge beams, retaining walls, utility poles, slabs, chimneys, tunnels and other structures requiring strengthening, stabilization or seismic upgrade. The use of externally bonded FRP sheets as reinforcement in concrete members has recently been investigated both theoretically and experimentally, showing a good promise of effective strengthening in view of the simplicity of application relative to bonding of steel plates. However, characterization of reinforcing effects in flexure and shear (Fig.20) has been behind many field applications. The strength of structural members reinforced by bonding FRP sheets depend naturally on the bonding or peeling strength between FRP sheets and structures. Evaluation of failure process and bonding strength against debonding or peeling is a matter of concern for structural reinforcement by FRP sheets.

A new peeling test of FRP sheets bonded on concrete was proposed to characterize the peeling strength and examine the effects of different surface treatment and primer. Maximum load and energy release rate due to peeling were evaluated from the viewpoint of fracture mechanics and theory of thin membrane as schematically shown in Fig.21 [10]. A simple data reduction method was proposed for the energy release rate due to peeling based on these considerations. The effect of surface treatment and primer was compared by energy release rate, initiation load and maximum load. Observing energy release rate and initiation load, it was shown that there were some differences between non primer and primer, and observing maximum load, it was shown that there were some differences among different surface treatments [10].



(a) Winding of sheet (b) Bonding of sheet (c) Bonding of laminates

Fig.19: Rehabilitation of infrastructures with FRP sheets or laminates as external reinforcements.

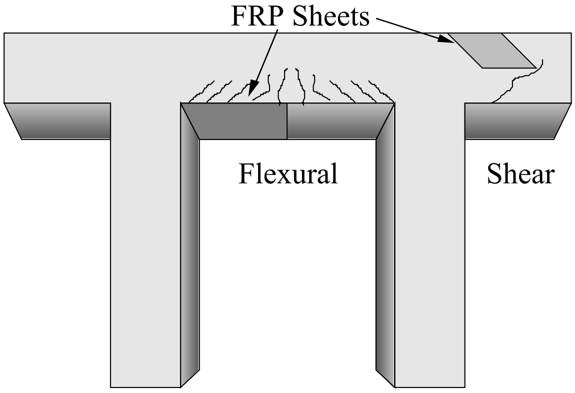
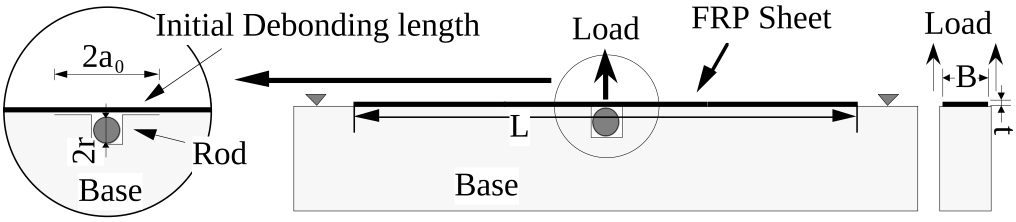
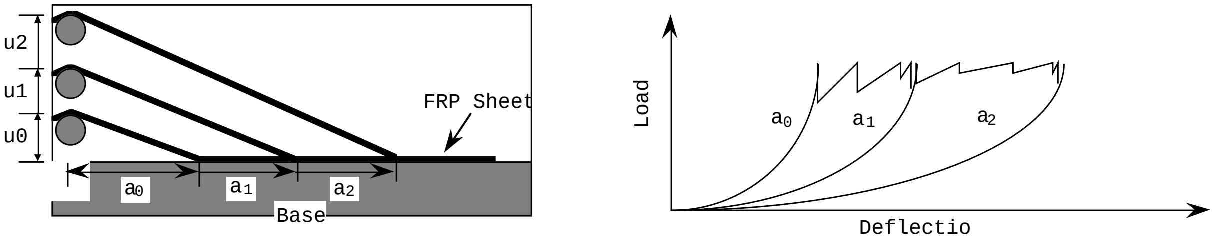


Fig.20: Reinforcing effects of FRP sheets in flexure and shear.



(a) Specimen and testing method



(b) Schematical load-deflection curves due to extension of debonding

Fig.21: Proposal of "Membrane Peeling (MP)" test of FRP sheet bonded on base material.

Towards Damage Tolerance Design

There has been a need for the criteria and methodology for Damage Growth Design (DGD) to maintain the flight safety of composite aircraft structures. The main purpose of DGD is how to estimate Time Before Catastrophic Failure (TBCF). Damages in composite structure are divided into the following 4 kinds by their sources: (a) Pre-existing Damage, (b) Damage Initiation, (c) Impact Damage, (d) Discrete Source Damage. DGD is needed for (a) ,(b) and (c) because of the origin of damage growth in service. For damage (d), the method similar to DTD of aluminum structure can be applied. For damage, the DGD method for growth from matrix cracks needs to be developed to know how long the strength can be maintained under increasing matrix cracks. As recent composite materials have very high fracture toughness, the damage sizes occurred by impact are smaller and are difficult to detect. For damage (c), the DGD method for growth from small impact damages also needs to be developed. The current design for composite structures is limited to no-growth.. The establishment of DGD method will have capability to design the life extended to TBCF. Structural design and technology improvement provide rational method for operators to achieve the extended utilization of aging aircraft by now and further to secure the flight safety of new designed aircraft in extremely long life service. Figure 22 shows a general flowchart to establish the DGD method for composite material structures [11].

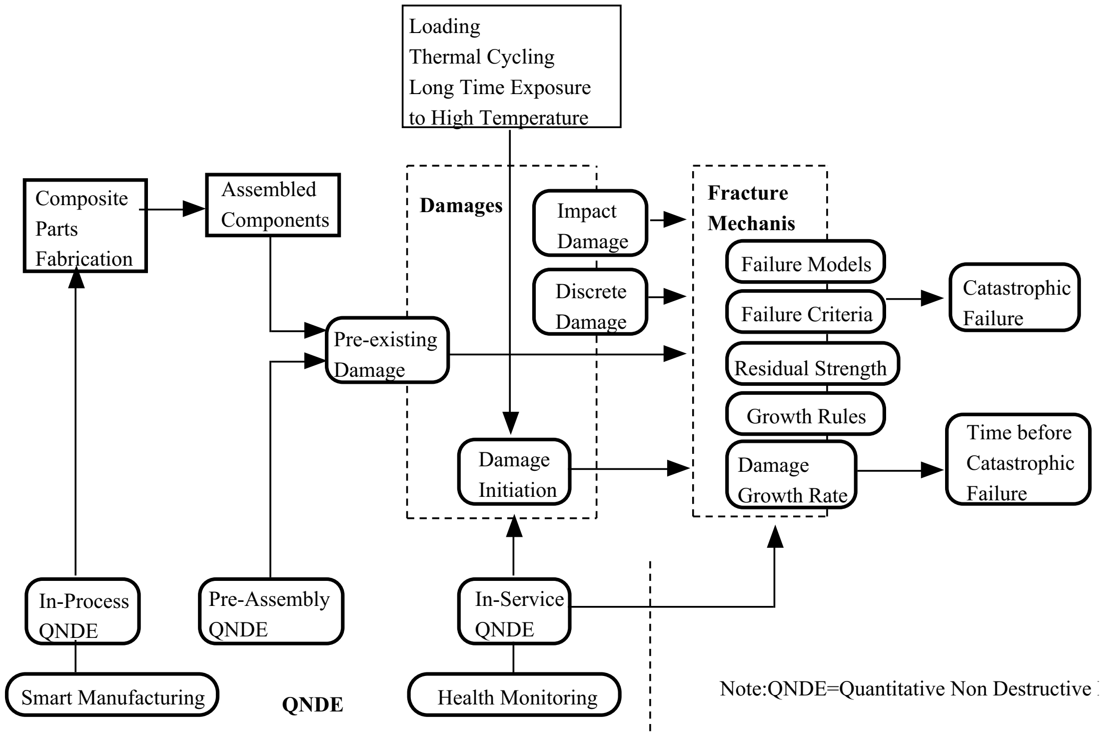


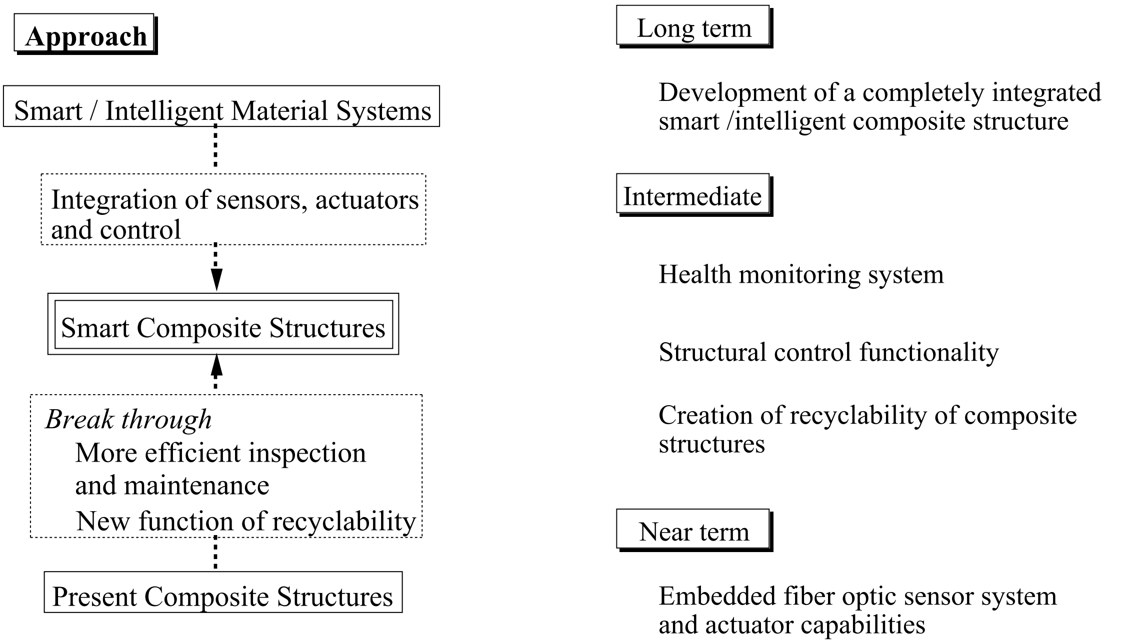
Fig.22: Damage growth design to estimate time before catastrophic failure of composite material structures.

HEALTH MONITORING OF COMPOSITE MATERIAL STRUCTURES

The new concept of the "smart" or "intelligent" material systems has been recently attracting a wide attention in the field of engineering materials and structures. As this conception has been defined in various ways for many fields of application, it appears that the common final goal has been directed toward developing a completely integrated structural system possessing adaptive functionality to external stimuli such as load and environment. From the viewpoint of structural materials, it appears that the two main targets have so far been of primary interest : structural monitoring and structural control with the aid of embedded sensor and actuator systems.

The realization of smart composite structures is considered to be advanced on the basis of long term, intermediate and near term targets due to various limitations in the available technology in sensor, actuator and control systems, as shown in Fig.23 [12]. Some intermediate and near term targets would be important in making a breakthrough in the present composite technology. Such examples are a health monitoring for more efficient inspection and maintenance of composite structures and also adding a new function of recyclability which is most lacking in the existing composite structures. The long term target should be the development of a completely integrated smart / intelligent composite structure. It is rather technological paradigm toward the integration of sensors, actuators and controls with a material or structural component as described above. It does not state a goal or objective of the system ; nor does it provide guidance how to create such a material system . For this reason, the intermediate and the near term targets should be evaluated from the practical viewpoint.

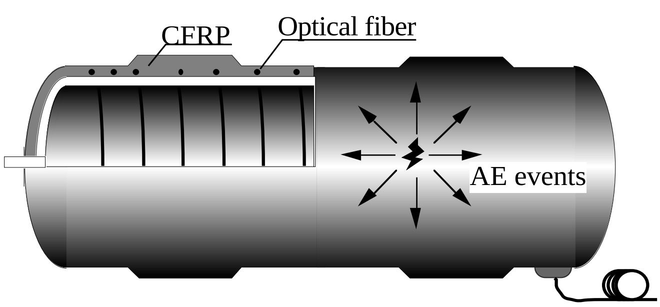
Among the intermediate targets, it is important to develop a health monitoring system in order to enhance safety and to offer cost savings due to more efficient inspection and maintenance of composite structures. Structural control functionality through the control of elasto-mechanical properties such as vibration and damping is another target to improve performance of composite structures. As the near term targets, various fundamental studies have been actively being advanced on embedded fiber optic sensor system and actuator system capabilities, for example, as shown in Fig.24 [13]. It has provoked a new problem of understanding the interaction characteristics between embedded sensors or actuators and composite host materials. As a result, the present state-of-the-art seems to be far from the optimum solutions. Hence new sensing and actuation elements are required.



(a) Two-way approaches to “smart” composite structures

(b) Long term, intermediate and near term targets

Fig.23: Concepts to realize "smart" composite structures.



(a) Schematic of AE detection using fiber optic sensor

(b) AE detection of FRP with embedded LDV sensor

Fig.24: Application of fiber optic sensor to detecting AE in composite materials.

CONCLUSIONS

Fusion of experimental and computational mechanics is essentially required to establish a more accurate modeling of a complicated damage progression of composite materials. This new approach has shown to be effective in improving the accuracy both in experimental and computational mechanics, which has so far been successful mainly in macro-mechanics. However, as the experimental micro-mechanics has recently been advanced, this hybrid approach will be extended to cover micro-mechanics in order to fill a still existing gap between micro- and macro-mechanics of composite materials. For this purpose, much attention should be directed toward the establishment of "intefacial mechanics".

The future role of composite materials in manufacturing industry would depend greatly on their possible adaptability with environmental harmonization as well as with the future innovative products design. The realization of multi-functionality would be important in the future composite technology including some smart functions, which would be made possible with the full use of their adaptability with versatile requirements.

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