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Review

Composite research and development in Korea

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Abstract—The recent research and development activities of some laboratories working on composite materials in universities (KAIST, Seoul National Univ., Postech, Gyeongsang National Univ.), research institutes (KIMM, KARI), and companies (Hankuk Fiber, DACC) are introduced in this article. Their activities cover a broad range of research and development fields in composite materials: design and fabrication; processing technology; structural analysis; characterization of composite materials; NDE; fiber optic structures; damage detection; health monitoring; smart structures and so on. These technologies will be increasingly used in various fields and the development of these technologies will play an important role in future industries.

Keywords: Design and fabrication; processing technology; NDE; fiber optic structures; damage detection; health monitoring; smart structures.

1. INTRODUCTION

It is my great pleasure to write a review paper on composite research and development activities in Korea to celebrate the first issue of the joint publication of the journal, *Advanced Composite Materials*, between JSCM (Japan Society for Composite Materials) and KSCM (Korean Society for Composite Materials).

Advances in science and technology require high performance materials, which can be specified by various criteria including less weight, more strength and lower cost. Composites are appropriate to these purposes and have become increasingly popular in Korea. A large number of research laboratories in universities, research institutes and industry have investigated composite materials. In this article, some remarkable research activities in universities (KAIST, Seoul National University, Postech, Gyeongsang National University), research institutes (KIMM and KARI), and industries (Hankuk Fiber, DACC) will be introduced.

Edited by the KSCM.

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2. RESEARCH ACTIVITIES OF KOREAN UNIVERSITIES

2.1. Intelligent Systems and Vibration Control Laboratory, KAIST

The Intelligent Systems and Vibration Control Laboratory (http://isvc.kaist.ac.kr) was established by Professor In Lee in 1987, and Professor Jae-Hung Han participated in the laboratory in 2003. Professors In Lee and Jae-Hung Han are working on smart materials, composite structures, structural dynamics, and aeroelasticity with more than 17 PhD and master course students and one Post-doctoral fellow. The ISVC lab was selected as a national research laboratory by the Ministry of Science and Technology in 2000.

The current research areas of the laboratory are as follows:

– Vibration control of smart materials and composite structures;
– Shape memory alloy and reconfigurable structures;
– Real time health monitoring using fiber optic sensors;
– Fluid–structure interaction problem;
– Aeroelasticity and aeroelastic control;
– Helicopter dynamics and rotor blade aeroelasticity;
– Stealth and smart skin.

Advanced structural systems can be optimized for corresponding applications. Hence, the ISVC laboratory has established many kinds of research programs to realize these functions of advanced structures. For example, functional materials and their characteristics, smart structures, sensor and actuator placement, controller design, and other relevant topics have been investigated.

The thermomechanical responses of the shape memory alloy hybrid composite (SMAHC) cylindrical panels are investigated to improve structural performance in a thermal environment (Fig. 1). The bucking and post-bucking behaviors of SMAHC cylindrical panels have been studied numerically under thermal excitation conditions. Additionally, some experimental studies on smart composite structures have been intensively carried out: vibration suppression of fiber optic smart structures, reconfigurable structures using shape memory alloys, stealth and smart skins.

The application of fiber optic sensor systems to vibration measurement and suppression is investigated (Fig. 2). Among several kinds of optical fiber sensors, extrinsic Fabry–Perot interferometer (EFPI) and fiber Bragg grating (FBG) sensors are applied. The dynamic sensing characteristics of fiber optic sensors are explored and the vibration measurement and suppression of composite structures have been investigated.

A smart composite wing is fabricated using SMA actuator and FBG optical fiber sensors (Fig. 3). SMA actuators make a deformation enough to improve the static and dynamic characteristics of the wing. The FBG sensor is successfully applied to the monitoring of unstable aeroelastic phenomena. The lift of the wing can

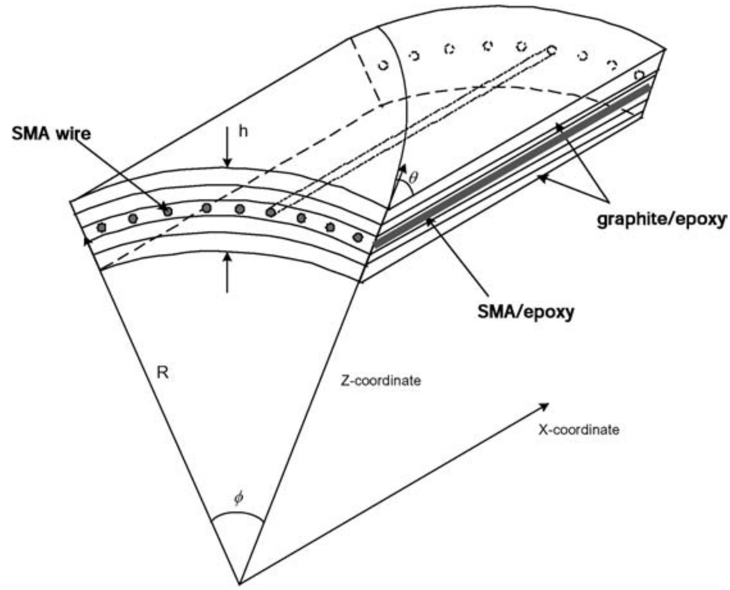


Figure 1. SMAHC shell structure.

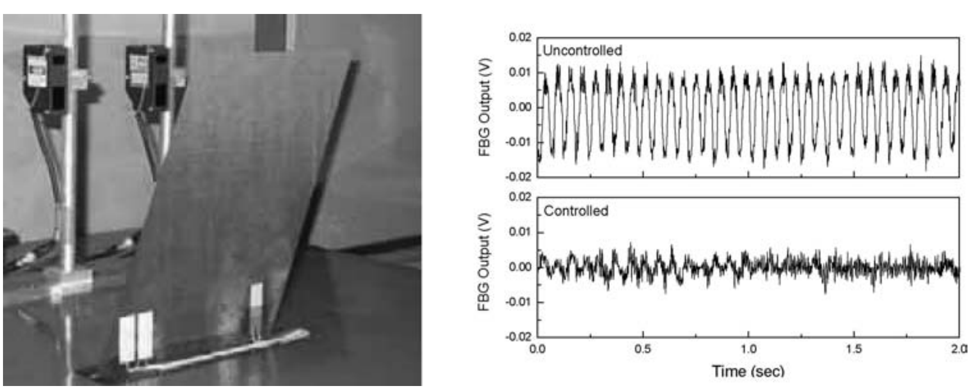


Figure 2. Flutter suppression using smart materials.

be greatly increased when electric power is applied. SMA actuators significantly reduce the amplitude of the limit cycle oscillation at the flutter speed. Real-time displacement signals are measured using the distributed FBG (Fiber Bragg Grating) sensors (Fig. 4).

For electromagnetic wave absorption technology (Fig. 5), sandwich type radar absorbing structures (RAS) are designed and fabricated in the X-band frequencies. As shown in Fig. 6, conductive fillers such as carbon black and MWNT (multi-walled carbon nanotube) are added to composite face sheets (glass fabric/epoxy composites and carbon fabric/epoxy composites) and polyurethane foam core.

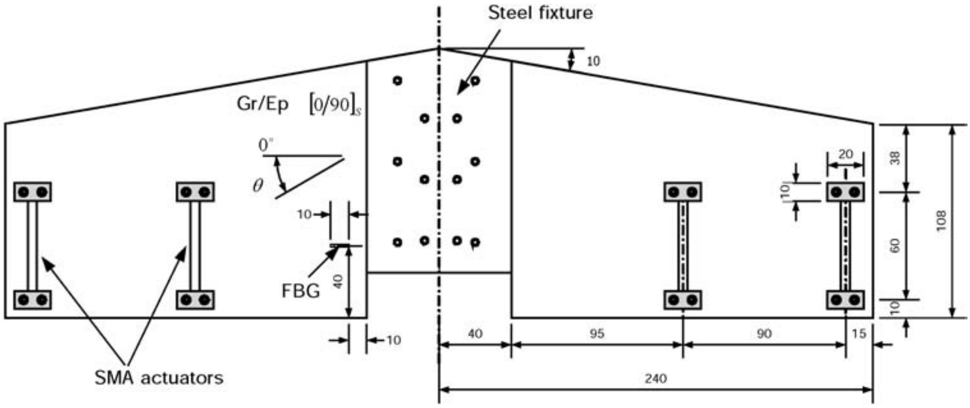


Figure 3. Smart composite wing.

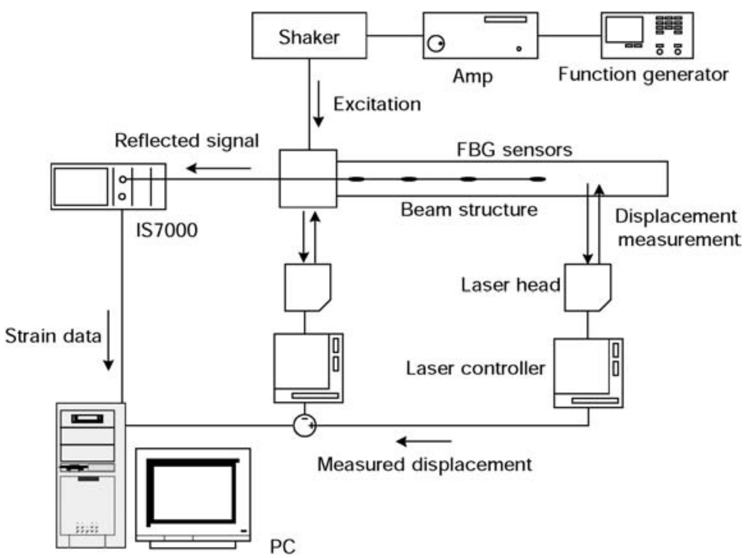


Figure 4. Real-time displacement measurement.

2.2. Mechanical Design Laboratory with Advanced Materials, KAIST

The research of the Mechanical Design Laboratory with advanced materials (http://scs.kaist.ac.kr) has been focused on the application of composite materials, such as automotive propeller shafts, composite robot end effectors for large LCD glass handling, and composite cure monitoring system. The laboratory has published 155 papers in the international SCI journals and 66 patents including 20 international patents have been registered under the supervision of Professor Dai Gil Lee. Professor Dai Gil Lee has supervised 24 Doctoral and 42 Masters degree students and is currently supervising 7 graduate students. He is a member of the Korean Academy of Science and Technology and Vice President of the Korea So-

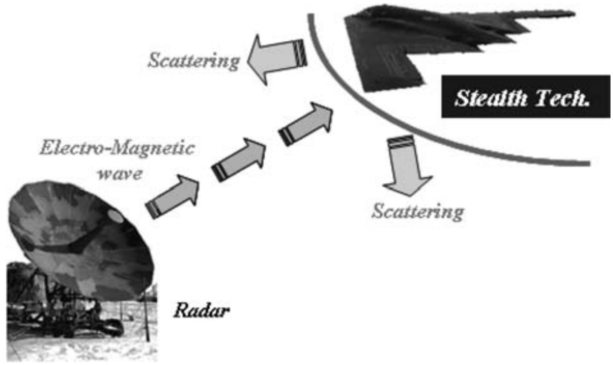


Figure 5. Diagram for stealth technology.

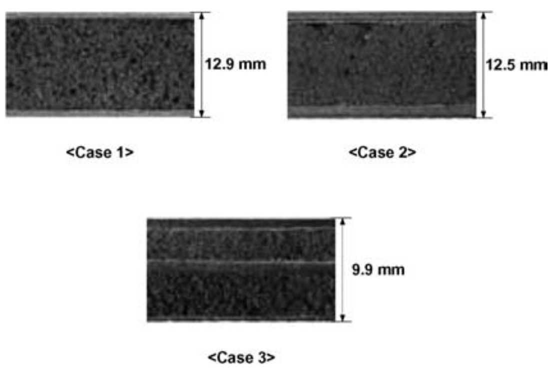


Figure 6. Sandwich radar absorbing structures.

ciety of Composite Materials. Oxford University Press published his textbook on 'Axiomatic Design and Fabrication of Composite Structures, Applications in Robots, Machine Tools and Automobiles', coauthored by Professor Nam P. Suh of MIT, 710 pages (2005). The book covers many industrial applications of composite structures, which have been obtained from their research results for more than 30 years.

The current research areas of the Laboratory are as follows:

- Construction of a database for joining and repairing advanced composite structures;
- Construction of the joining surface science model;
- New damage monitoring using piezo-electricity;
- Smart cure monitoring for advanced composite materials and adhesively bonded joints;
- Expert system for joining and repairing of structures made of advanced composite materials;
- Development of composite hemispherical bearings;

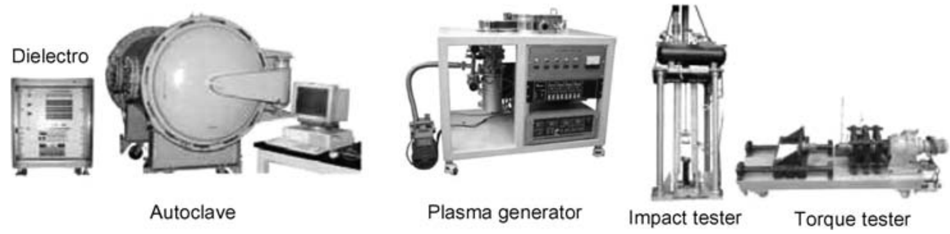


Figure 7. Facilities of laboratory.

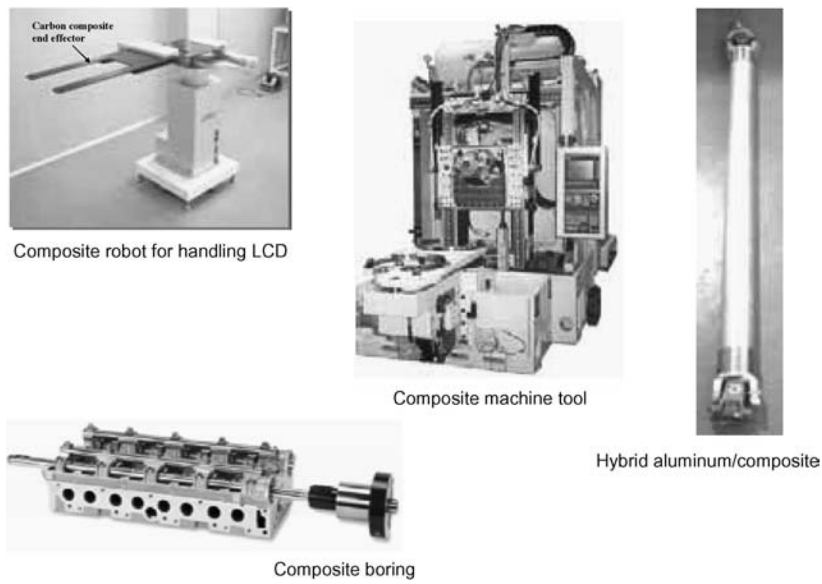


Figure 8. Industrial applications of composite structures.

- Development of composite automotive propeller shafts;
- Stealth application and electromagnetic properties of composite materials;
- Composite nozzle dam analysis.

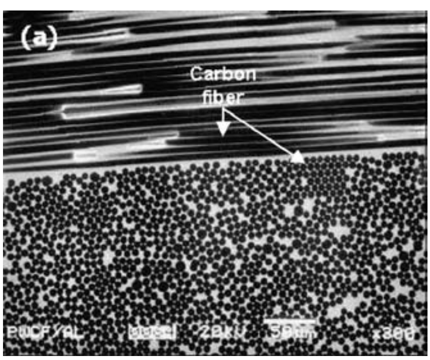
The above authors constructed a valuable database and failure model for adhesively bonded joints using surface science for the first time. Figure 7 shows the equipment of the laboratory, such as the autoclave for manufacturing composite material, 16-channel dielectrometry for cure monitoring, torque tester, impact tester and plasma generator for surface treatment. Some successful industrial applications of composite structures such as a composite robot, a machine tool and a hybrid propeller shaft are shown in Fig. 8.

2.3. Composite Materials Laboratory, KAIST

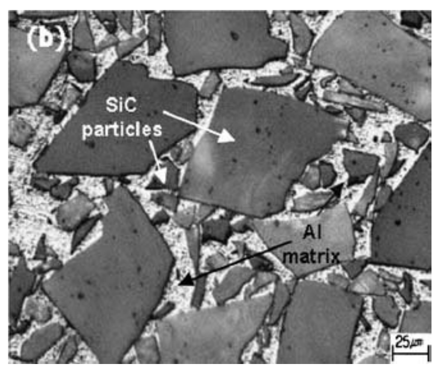
The Composite Materials Laboratory (http://composite.kaist.ac.kr) was established by Professor S. H. Hong at KAIST in 1990, and now there is 1 post-doctoral fellow, 7 PhD candidates and 5 MS students. The Composite Materials Laboratory has been investigating fabrication processes and applications of composite materials, especially focused on metal matrix and ceramic matrix composites, and nanocomposites. The main current research topics are given in the next sections: design optimization, fabrication process and characterization of composite materials, and development of molecular level synthesis process for nanocomposites.

2.3.1. Design optimization, fabrication process and characterization of composite materials. Fabrication of carbon fiber/Al and SiCp/Al composites has been investigated by the pressure infiltration casting and powder metallurgy processes (Fig. 9). Carbon fiber/Al and SiCp/Al metal matrix composites with controlled thermal conductivities and CTEs are under development for thermal management materials for electronic packaging applications.

A fabrication process for oxide dispersion strengthened tungsten heavy alloy has been developed by a mechanical alloying and two-step sintering process (Fig. 10). The developed ODS tungsten heavy alloy shows static and dynamic



(a)



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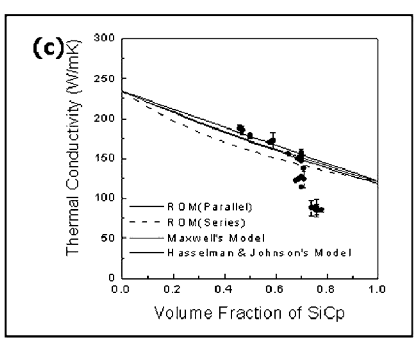
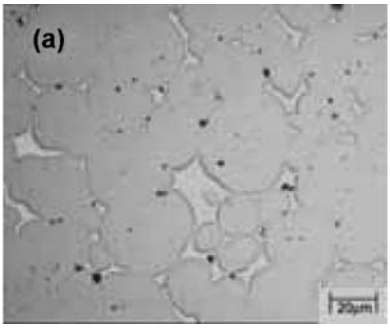
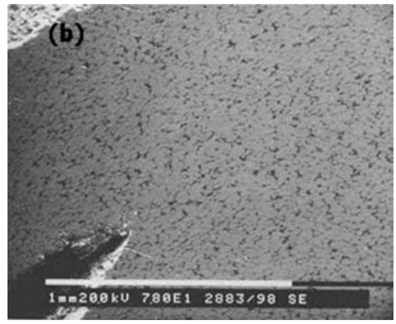


(c)

Figure 9. Metal matrix composites as thermal management materials. (a) Microstructure of carbon fiber/Al composite. (b) Microstructure of SiCp/Al composite. (c) Thermal conductivities of SiCp/Al composites.



(a)



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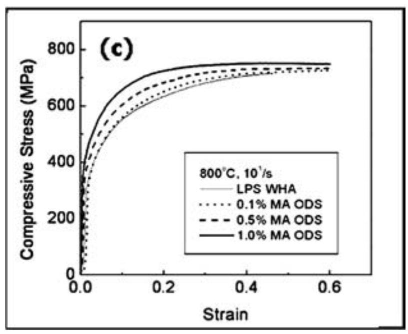
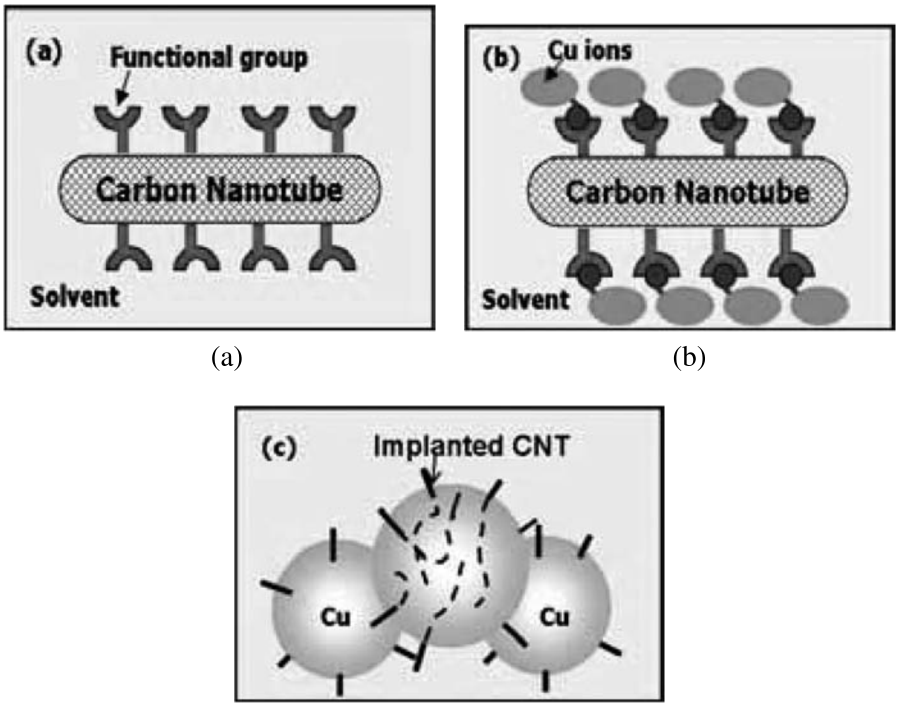


(c)

Figure 10. Microstructure and mechanical property of ODS tungsten based composite. (a) Microstructure of ODS tungsten heavy alloy. (b) Fractography of ODS tungsten heavy alloy. (c) High temperature compressive test results of ODS tungsten heavy alloy.

mechanical properties. Oxide dispersion strengthened tungsten heavy alloy is under development by changing the process parameters in company with AFRL.

2.3.2. Molecular level synthesis process and properties of nanocomposites. A novel fabrication process called 'molecular-level synthesis' for fabrication of CNT/metal and CNT/ceramic nanocomposites, in which CNTs are homogeneously dispersed in matrix materials has been developed. This process involves suspending CNTs in a solvent by surface functionalization, mixing matrix ions with the CNT suspension, drying, calcinations and reduction (Fig. 11). The CNT/Cu nanocomposites showed remarkably enhanced yield strength and elastic modulus compared to those of unreinforced Cu. CNT/Co and CNT/alumina nanocomposites were successfully synthesized using the process. The CNT/Co nanocomposites are under development as emitter materials for field emission display or back light unit applications.



(a) (b) (c)

Figure 11. Molecular level synthesis process of CNT/Cu nanocomposite. (a) Functionalization of CNTs. (b) Molecular level mixing of CNTs with Cu ions. (c) CNT-implanted Cu nanocomposite powders.

2.4. Smart Structures and Composites Laboratory, KAIST

The Smart Structures and Composites Laboratory (http://smartech.kaist.ac.kr) has more than 10 MS and PhD students working on analysis and design of composite structures, development of advanced composite materials, and evaluation of smart structures using damage detection and health monitoring.

2.4.1. Development of composites for cryogenic use. For carbon fiber reinforced composites to be effectively applied to cryogenic propellant tanks, it is indispensable to have knowledge of their behavior in a cryogenic environment, such as stiffness, strength, and crack resistance, and to develop the most suitable composite systems for this application. After adding MWNT (multi-walled carbon nanotube) fillers into the composite resin, we could get better crack resistance at cryogenic temperatures (Fig. 12). In order to get the cryogenic characteristics of the behaviors of filament wound cryogenic tanks, we tested ring specimens consisting of a composite and aluminum liner (Fig. 13). Now we plan to fabricate and test a prototype tank using the developed composite systems for cryogenic use. Finally, fiber optic

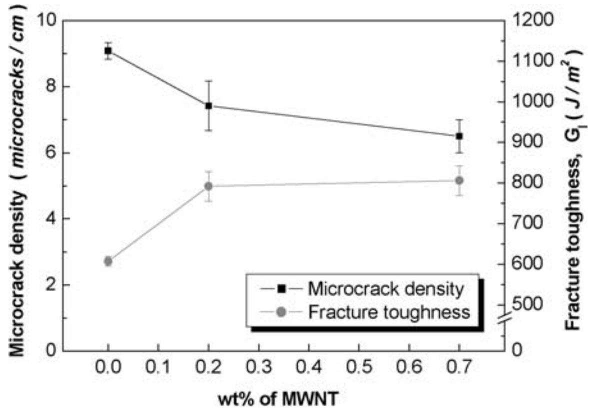


Figure 12. Effects of MWNT on microcrack density and fracture toughness.

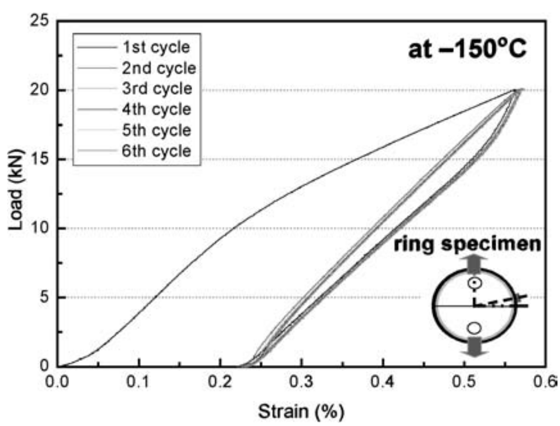


Figure 13. Load–displacement curve of composite–aluminum ring specimen at cryogenic temperatures.

sensors are used to monitor the structural health status of the cryogenic propellant tank.

2.4.2. RCS (Radar cross-section) reduction technology. The object of the design of multi-layered composites for the minimization of RCS is to develop the radar absorbing structures (RASs) with load bearing ability in the hostile frequency band (Fig. 14). We fabricated MWNT (multi-walled carbon nanotube)-filled glass/epoxy woven composites to design two-layered RASs with a 10 dB absorbing bandwidth in the whole X-band and with mechanical properties of each layer intact or improved (Fig. 15). Its thickness is 3.27 mm. A study in progress aims to broaden the absorbing bandwidth of a multi-layered RAS with a frequency selective surface (FSS). An electromagnetic field analysis of FSS is in progress in order to reach this goal.

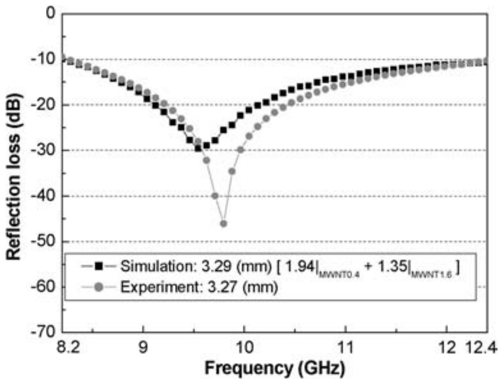


Figure 14. Reflection loss of two-layered RAS with 3.27 mm thickness.

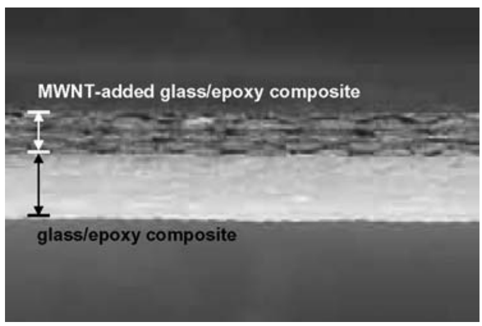


Figure 15. Cross-section of two-layered RAS of MWNT added composites.

2.4.3. Non-destructive evaluation of smart composites. The objective of this research is the development of a non-destructive evaluation system of smart composite structures using optical fiber Bragg grating (FBG) sensors. This real-time health monitoring technology will improve the efficiency of the conventional NDE methods by sharing the history of the impact damages and strains from *in-situ* health monitoring (Fig. 16). The statistical data of the AE events will estimate the correct lifetime of the structures. The signal characteristic of the external impact is also analyzed for damage assessment. This technology has been applied to the composite wing model and bolt joints of composite plate and filament wound composite pressure vessels (Fig. 17).

2.4.4. Fiber optic sensor technology. This novel optical fiber sensor simultaneously measures strain and temperature (Fig. 18). The sensor is formed by two fiber Bragg gratings, which are written in optical fibers with different core dopants. The two gratings were spliced close to each other and the sensing element resulted in Bragg gratings of similar strain sensitivity but different response to temperature (Fig. 19). Also, several factors influencing the mechanical strength of FBG

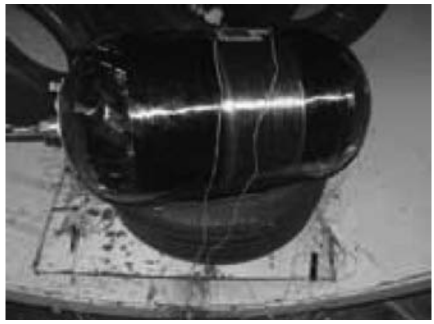


Figure 16. Hydrogen storage composite pressure vessel with embedded FBG sensor arrays.

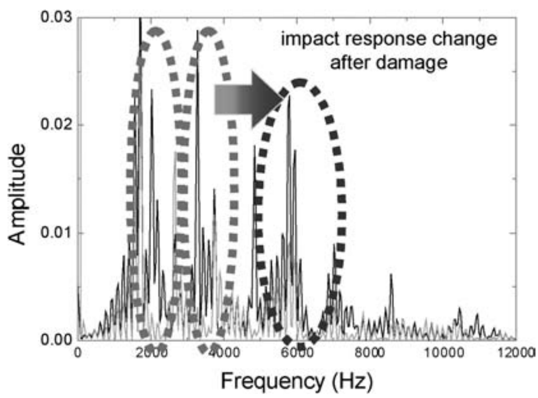


Figure 17. Damage evaluation of composite pressure vessel using impact response spectrum.

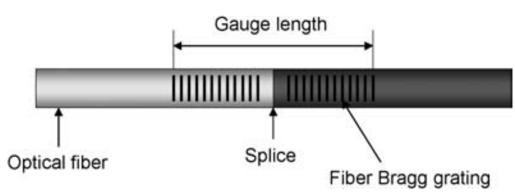


Figure 18. Design of FBG based sensor for temperature and strain discrimination.

sensors during their fabrication were examined and FBG sensors were made with sufficiently great mechanical strength.

2.4.5. Analysis and optimal design of composite structures. FE analysis and optimal design of composite structures are demanded for various fields of composite application to design and verify a structural or thermal stability. A post-buckling analysis of a composite stiffened panel was performed with regard to progressive failure and stiffener debonding (Fig. 20). The stacking sequence and angle was optimized using modified GA and metamodel methods. Also, we conducted structural and modal analysis to verify the structural safety of the composite

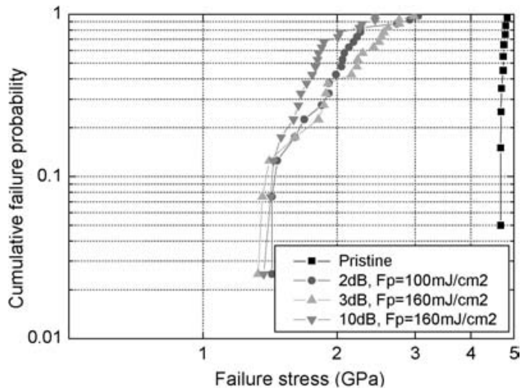


Figure 19. Weibull plots for FBG sensors with different reflectivity.

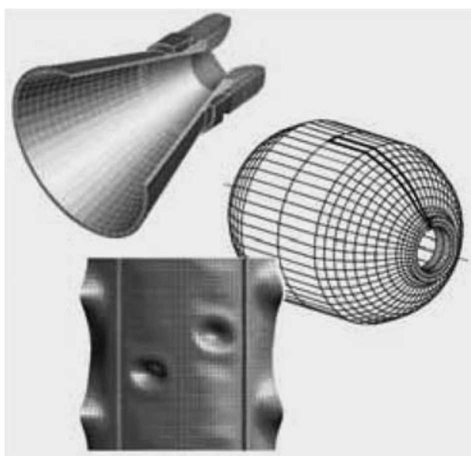


Figure 20. Finite element models for structural analysis and optimization of composite nozzle, fuel tank, and stiffened panel.

structures of Tilting Train eXpess (TTX) and optimal design for car body weight reduction (Fig. 21).

2.5. Aerospace Structures Laboratory, SNU

The Aerospace Structures laboratory (http://aeroguy.snu.ac.kr) was established in 1986 by Professor S. J. Kim. The principal objective of this laboratory is a structural analysis and design of aeronautical systems. To achieve this goal, more than 20 researchers are working on numerical and experimental studies.

2.5.1. Material characterization and impact simulation — DNS (direct numerical simulation, cross-ply laminates, 3D orthogonal woven and active fiber composite). For a complete description and prediction of structural behaviors of real composite structures, DNS on composites is proposed. DNS is based on the full microme-

Figure 21. FE analysis to design and verify the structural safety of composite car body of Tilting Train eXpress (TTX).

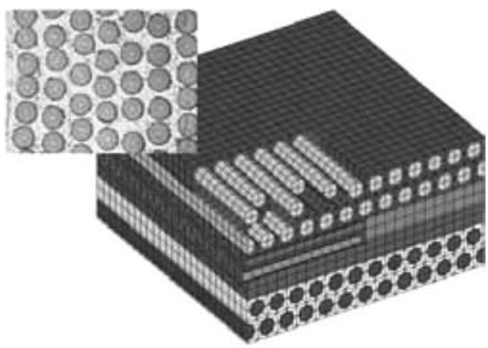


Figure 22. A micrograph of a cross-section of boron/aluminum fiber reinforced laminate.

chanics considering constituents such as fiber and matrix, respectively, and leads to successful applications for various composite materials such as cross-ply laminates (Fig. 22), 3D orthogonal woven composites and active fiber composite (AFC) materials considering the realistic features such as fiber–matrix geometry and piezoelectric characteristics (Fig. 23). Numerical material characterization and dynamic low velocity impact simulations are conducted using a large-scale finite elements solver such as parallel multi-frontal solver in high performance computing configurations. The predicted material properties that are based on DNS produce better correlations with the experimental results as against classical approaches such as the unit cell method using a representative volume element for fiber reinforced laminates or laminate block for woven composites. Using the DNS model, transient response analysis on the composite plates subjected to low velocity impact loading is conducted to obtain the microscopic in-plane and inter-laminar stress behaviors inside the materials, which would have been unattainable using the traditional homogenized approach.

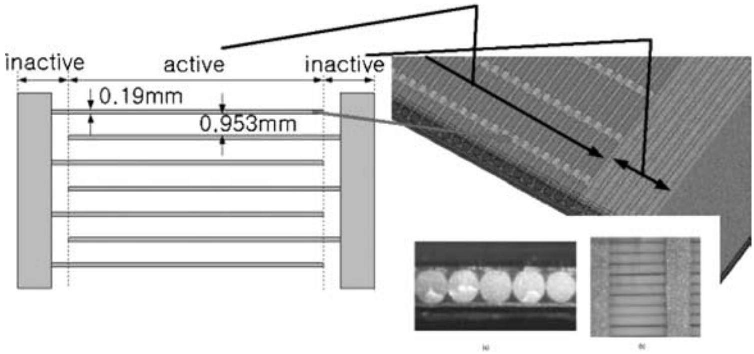


Figure 23. AFC pack inter-digitated electrode pattern and its location.

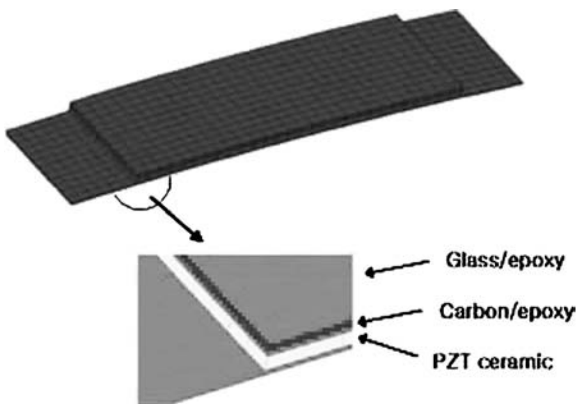


Figure 24. Composite curved piezoelectric actuator.

2.5.2. Composite curved piezoelectric actuator. The electromechanical displacements of curved piezoelectric actuators composed of PZT ceramic and laminated composite materials are calculated based on high performance computing technology and the optimal configuration of composite curved actuator is examined. To accurately predict the local pre-stress in the device due to the mismatch in coefficients of thermal expansion, carbon-epoxy and glass-epoxy as well as PZT ceramic are numerically modeled by using hexahedral solid elements (Fig. 24). Because the modeling of these thin layers increases the number of degrees of freedom, large-scale structural analyses are performed through the Pegasus supercomputer, which is installed in Seoul National University. In the first stage, the curved shape of the actuator and the internal stress in each layer are obtained by cured curvature analysis. Subsequently, the displacement due to the piezoelectric force (which is produced by applied voltage) is also calculated (Fig. 25). The performance of the composite curved actuator is investigated by comparing the displacements obtained by the variation of thickness and elastic modulus of laminated composite layers. In order to consider the finite deformation in the first analysis stage and include the

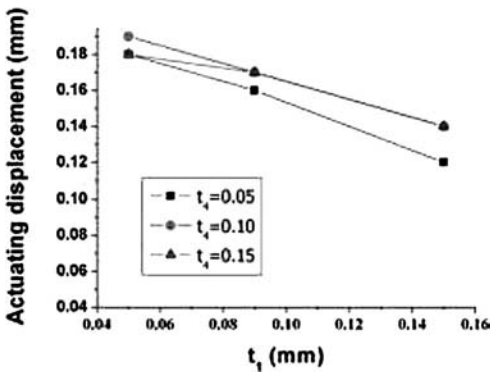


Figure 25. Actuating displacement according to the change of the thickness of glass/epoxy layer at the bottom.

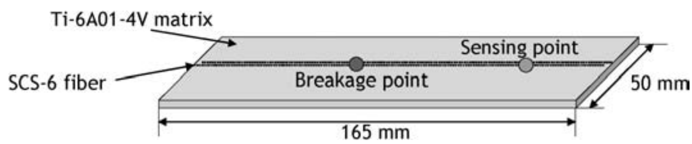


Figure 26. Plate with a single SCS-6 fiber.

pre-stress due to the curing process in the second stage, nonlinear finite element analyses are carried out.

2.5.3. Simulation of acoustic emission. Understanding and modeling the damage process have been valuable tools in damage assessment and in the design of composite structures. The high velocity and the small wavelength of the acoustic emission require a refined analysis with dense distribution of the finite element and a short time period (Fig. 26). In order to fulfill the requirement for capturing the exact wave propagation and to cover the 3D simulation, parallel finite element transient impact analysis code and high performance computing (HPC) technology should be considered. To this end, a new approach for a numerical modeling of acoustic emission induced by impact loading in a composite material is proposed by considering the combination of finite elements and composite damage criterion. A numerical experiment is conducted to simulate the full procedures from the impact phenomenon to the damage-induced acoustic emission wave (Fig. 27). The numerically reproduced wave signal is transformed by wavelet transform to analyze the frequency and the resolution characteristics between the acoustic emission signals of various damage mechanisms (Fig. 28).

2.5.4. Non-destructive evaluation — TSA (tapping sound analysis). A new NDE method that uses a numerically simulated tapping sound as the reference data was proposed and designated as Tapping Sound Analysis (Fig. 29). TSA is composed of the analysis of dynamic behaviors, tapping sound calculations, and the detection of

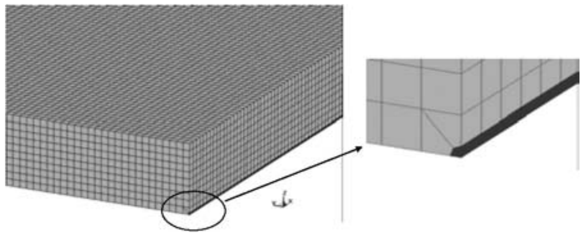


Figure 27. FE model of single fiber composite (1/8 model).

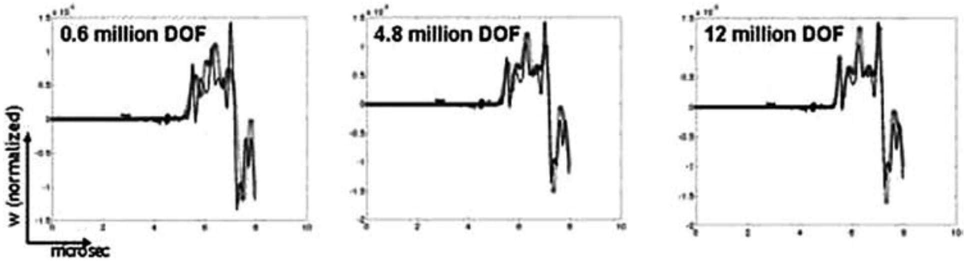


Figure 28. Time history of displacement induced by fiber breakage (— experiment, ○ present).

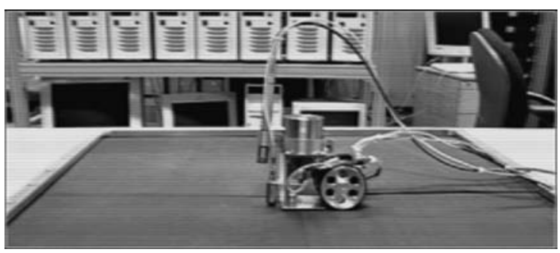


Figure 29. Experimental apparatus for TSA.

internal defects. Dynamic behaviors are obtained from a transient time integration scheme using finite elements, and the tapping sound radiated from the vibrating surfaces of the test structure is measured by the boundary element method. The detection of an internal defect is carried out by comparison of the tapping sounds using the feature extraction method based on the wavelet packet transform. TSA demonstrates that the internal damage of laminated composite plates is numerically well detected and simulated successfully in accordance with the experimental results (Fig. 30).

2.6. Textiles and Composites Laboratory, SNU

The Laboratory of Textiles and Composites (http://textile.snu.ac.kr) was established in 1985. The LTC has participated in the Intelligent Textile System Research Center (ITRC) which is supported by the MOST/KOSEF (Ministry of Science and Technology/Korea Science and Engineering Foundation). The focus of this laboratory is on the manufacturing process and physical properties of advanced

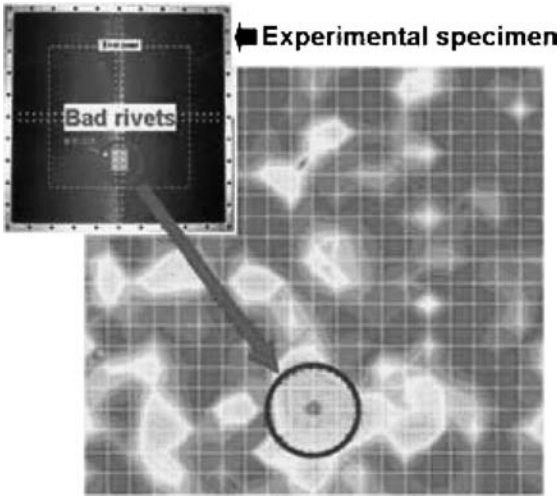


Figure 30. Feature image for the damage detection.

fiber-reinforced composite materials. Recently, the LTC conducted a study on multi-axial textile composites. They developed a three-dimensional circular braiding machine and a CAD system for modeling a 3D braided structure, and analyzed the mechanical properties of the composites. In addition, the internal and residual strain was assessed using embedded optical fiber sensors. They have also developed and optimized the manufacturing process of spun carbon yarn, fabric and their composites including a hybrid structure system focusing on characterization and prediction of the thermal, ablative and mechanical properties.

A geometric study for the 3D braided composite was performed (Fig. 31). Yarn paths were described using the third order spline, and the unit cells as well as the representative volume element (RVE) were determined. Finally, the CAD system for the 3D circular braided preform was developed and parametric studies have been performed (Fig. 32). The mechanical analysis for the composite was carried out using the volume averaging method and compared with experimental measurements (Fig. 33).

FBG sensors were embedded along the curved braid yarn as well as in the axial or principal directions, using the resin transfer molding (RTM) process (Fig. 34). During the curing process, the dimensional changes that were induced by the thermal and chemical effects were monitored. The internal strain at room temperature during the compressive test was estimated using embedded FBG sensors. The results from the FBG sensor were very close to the data from the electric strain gauges that were bonded on the surface. Using embedded FBG sensors and surface-bonded strain gauges, the internal strain of 3D braided composite was estimated during compressive and bending tests. The released residual strain was measured using the cutting method. Once the relationship

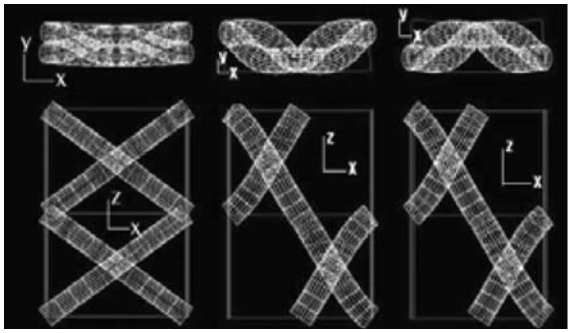


Figure 31. The graphical development of unit cells of braid.

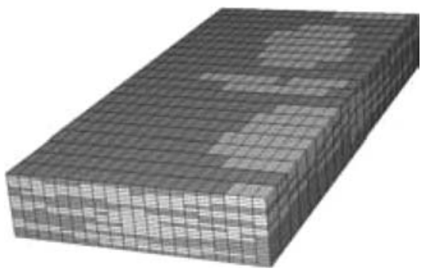


Figure 32. FEM mesh of hybrid braid composite.

Figure 33. Compressive test for hybrid braid composite.

between the thermal contraction and residual strain was determined, the residual stress could be estimated using the nondestructive method.

They performed an impact analysis of composite structures. For this research, various kinds of fibers and mechanical configurations are applied to modify the final preform structure.

For insulated applications such as a solid rocket motor, the development of carbon fiber reinforced composites that have relatively low thermal conductivity become more important. Introducing the spun yarn type PAN-based carbon fibers could be a possible way to replace the filament yarn type carbon fibers. This laboratory also performed numerical modeling of the effective thermal conductivity of spun carbon

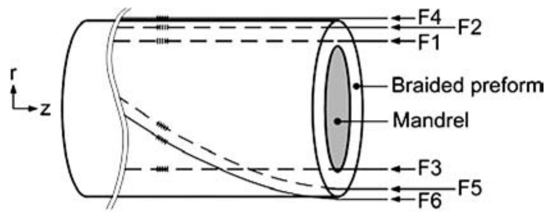


Figure 34. Embedded location of FBG sensors.

Figure 35. Spun carbon yarn.

Figure 36. Continuous carbon filament.

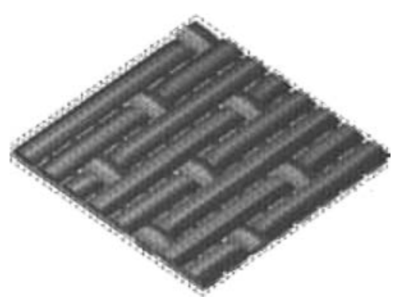


Figure 37. Woven fabric composite.

yarn and woven fabric composites reinforced with spun carbon yarn (Figs 35, 36, and 37).

2.7. Composites Manufacturing Laboratory, SNU

The Composites Manufacturing Laboratory (http://composite.snu.ac.kr) is supervised by Professor Woo Il Lee and has a membership of 15 researchers comprising 8 PhD students and 7 MS students. This research group has been studying various composite manufacturing processes for affordable and cost-effective mass production methods. Experimental and analytical investigations have been carried out for autoclave molding, resin transfer molding, compression molding, filament winding and pultrusion processes.

2.7.1. Liquid molding process. Different aspects of the liquid molding process are studied for methods such as resin transfer molding (RTM), vacuum assisted RTM and compression/resin transfer molding processes. Also, the behavior of permeability under different conditions is investigated.

Different techniques have been attempted to enhance the performance of analysis methods of resin flow during RTM processes. Numerical improvements were achieved by introducing refinement of the mesh in the resin front region to reduce errors in solving the moving boundary problem in RTM using fixed numerical grids. A 3-dimensional flow and thermal analysis was performed to simulate the RTM fabrication of thick composite parts (Fig. 38). A fiber-optic sensor system was developed to detect the location of flow front in thick composites during RTM fabrication. In order to characterize the preform more accurately, discrepancies in permeability for different measurement methods were investigated.

In an effort to enhance the fiber volume fraction and the rate of production in RTM, a number of modified methods were tested. The resin transfer/compression molding (RT/CM) process, in which the resin injection and the mold closing are carried out in two steps, was found to be efficient for enhancing the flow rate and the fiber volume fraction. For an optimal design of the RT/CM process, numerical simulation was performed and compared with the experimental force data. Another modification of RTM was investigated for a rapid manufacturing of high-fiber ratio products. Two different multiple-gate injection schemes were practiced: a progressive opening of the gates as the resin front advances, and the control of the injection pressure at each gate as a function of time. It was found that this method was effective in reducing the mold filling time for a given fiber volume fraction.

The vacuum-assisted resin transfer molding (VARTM) process was investigated to analyze the resin flow in the dual-layer flow medium with a sacrificial layer as a flow aid medium.

Analysis has been performed to estimate the distribution of microvoids in RTM products. The mechanism of void generation was modeled by introducing the

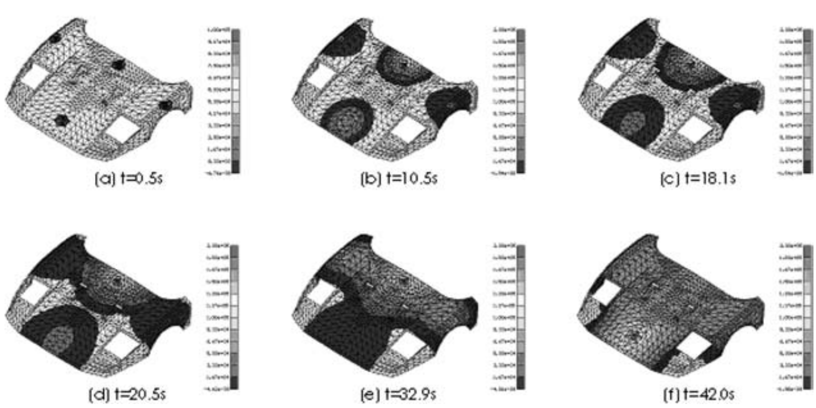


Figure 38. Pressure modulated multiple gates resin injection of RTM process.

capillary number as the major parameter. A unified analysis for the macro- and micro-voids in composites is currently underway. The effect of a vacuum in the formation and transport of macro- and micro-voids in the RTM process is being investigated.

2.7.2. Pultrusion process. The thermosetting composite pultrusion process was also investigated (Fig. 39). Mathematical models were developed for the wetting and the curing of thermosetting resin into fiber bundles. Experiments were performed to measure the pulling force required for different pulling speeds and mold temperatures, and the numerical prediction was verified by comparison with the experimental data. Also, the pultrusion process of phenolic foam composites was analyzed.

2.7.3. Carbon–carbon composites. For thick carbon–carbon composites, a mathematical model was developed to predict the degradation of mechanical properties subject to a short-term aging at high temperatures. In addition to the analysis of free-surface flows, a finite element analysis was performed for the incompressible viscous flow by using a selective volume-of-fluid method.

2.7.4. Other composites manufacturing methods. A model was developed for the impregnation of thermoplastic composites using commingled yarns of thermoplastic fibers and glass fibers. The orientation of short fiber reinforcements in the compression molding process was analyzed to predict the direction of fiber alignment in compression-molded products.

2.7.5. Free surface tracking algorithms. Along with the composites processing techniques, the group also paid attention to general free surface problems (Fig. 40). They investigated the non-isothermal injection molding of molten polymers using the finite element method and another finite element analysis of the injection mold filling process considering the phase change in the polymer melts near the mold wall. The analysis technique was applied to general free surface flows covering a wide range of Reynolds numbers.

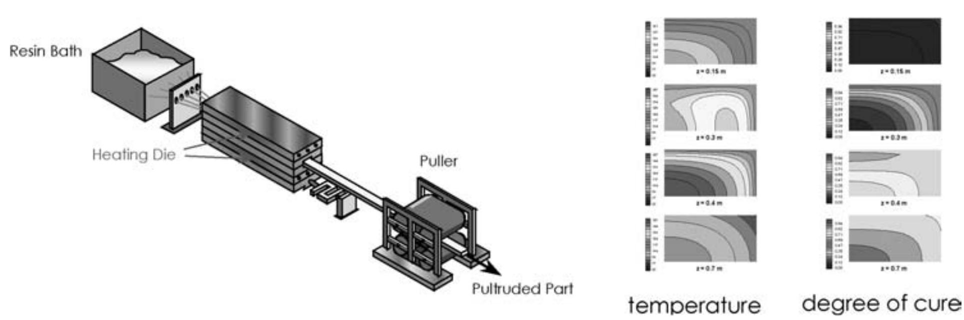


Figure 39. Thermosetting pultrusion process.

2.8. Advanced Composites and Structural Design Laboratory, POSTECH

The ACSD laboratory at POSTECH (http://www.postech.ac.kr/me/cm) was initiated in 1987 by Professor K. S. Han and various research projects in the field of composite materials have been conducted. The long-term research strategy of the ACSD laboratory is to promote the understanding and use of composite materials, and finally, they want to provide an accessible knowledge and technology base.

2.8.1. Numerical simulation of fabrication procedure. Squeeze casting is one of the basic manufacturing processes of metal matrix composites. Since there are many variables in this process, numerical simulation is useful in obtaining a high quality casting product. For the simulation of heat transfer and fluid flow during casting, we are developing a finite element model that can cover all the components during the squeeze casting process (Fig. 41). The numerical solutions for the infiltration and solidification of complex 3D components correlate very well with the experiments.

2.8.2. Fabrication and application of conductive polymer composites. Conductive polymer composites for bipolar plates of PEM fuel cells offer the potential advantages of lower cost, lower weight, and easier manufacturing than traditional graphite and metal plates. We are developing the fabrication process of conductive polymer composites with high filler loadings and systematic approaches on various kinds of graphite particles. Developed bipolar plates at the current stage were shown to have excellent electrical conductivity, flexural strength, and chemical and thermal stability (Fig. 42).

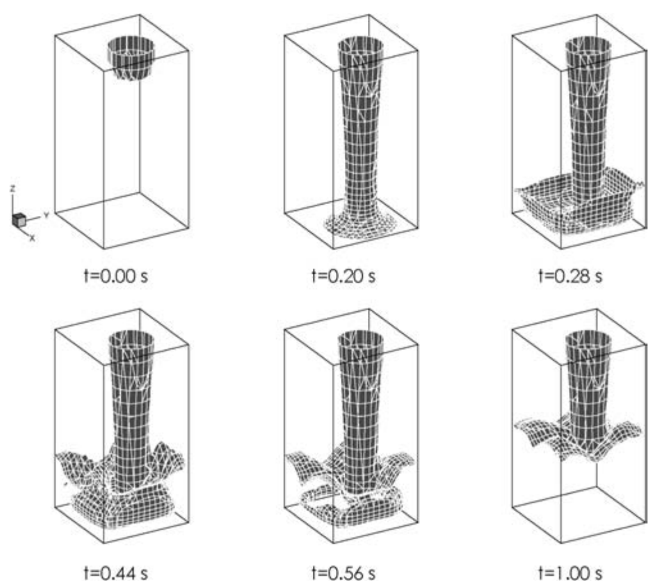


Figure 40. Simulation of free surface flows.

2.8.3. Structural design and optimization. A composite blade using GFRP was developed for a 750 kW wind energy conversion system. The blade was designed to withstand various types of relevant loads, such as static loads, buckling stability, natural frequency, blade tip deflection at various rotation speeds, and so forth (Fig. 43). For lightweight design, the thickness and lay-up pattern of the skin-form sandwich structures were optimized.

2.8.4. Metal matrix composites and applications. The laboratory has studied the processing method, micromechanics, mechanical behavior and applications of metal matrix composites (MMCs). This research experience assisted the development of fiber/particle hybrid MMCs which are low cost and have improved properties for practical use. Currently, preliminary research in nanofiber-based metal matrix composites is being undertaken together with evaluation technology in nano-scale for various characteristics.

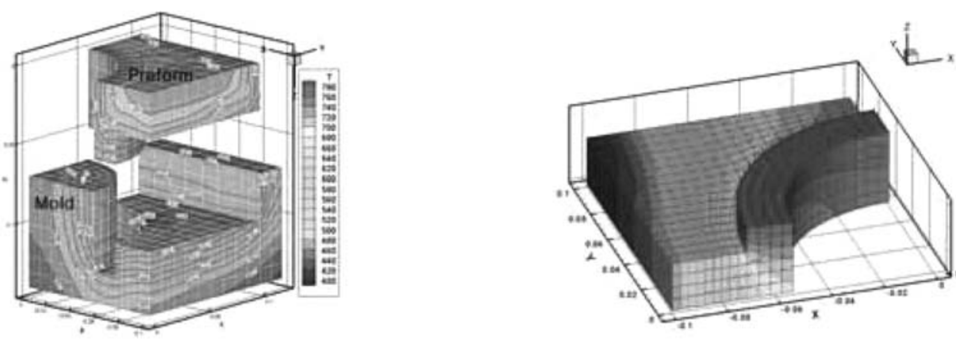


Figure 41. Numerical simulation of squeeze casting process.

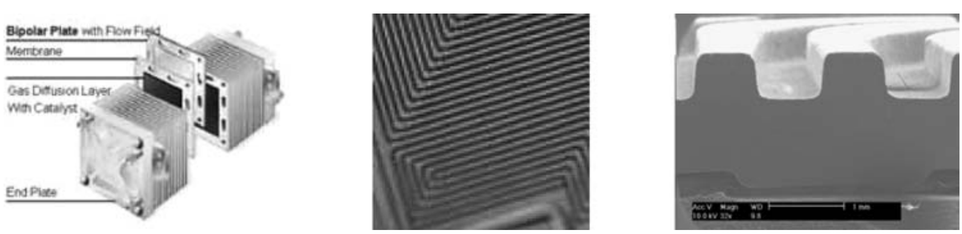


Figure 42. Bipolar plate of fuel cells.

Figure 43. Rotor blade for wind turbine and its static/buckling analysis.

2.9. Nano-Structures and Composites System Laboratory, POSTECH

The Nano-Structures and Composites System Laboratory (http://nscs.postech.ac.kr) has been working on the development, design and application of advanced composites. Experiments, development of manufacturing process, and structural design related to composite materials are the main research topics in the NSCS. Recently, Professor W. B. Hwang, who is the supervisor of this laboratory, has concentrated on two research subjects. One is to develop antenna structures using microstrip antenna elements and a composite sandwich structure for application on car roof panels. The other is to design, fabricate, and characterize nano-honeycomb structures in terms of their structures and properties in nanometer scale.

2.9.1. Composites–smart–structures for future innovative communication. The structural surface becomes an antenna. The embedding of radio frequency (RF) antennas in a load-bearing vehicle's skin is a new approach to the integration of antennae into structural body panels. It emerged from the need to improve structural efficiency and antenna performance. It demands integrated product development from disparate technologies including structures, electronics, materials and fabrication in order to generate a realistic design. To reach the goal of composite-smart-structures applied to land-vehicle roof panels the studies on multifunction, conformal and electrically beam-steerable antennae must be carried out. Figure 44 shows 16 × 16 array antenna elements inserted in a surface antenna-structure for satellite communication at a central frequency of 12.5 GHz.

2.9.2. Characterization of nano-honeycomb structures. Honeycomb structures with the pores of a nanometer size were referred to as nano-honeycomb structures as shown in Fig. 45. The nano-honeycomb structures can be used more widely than the honeycomb cell structure of macroscale in the new fields of magnetic storage, solar cells, carbon nanotubes, catalysts, and metal nanowires. They fabricated

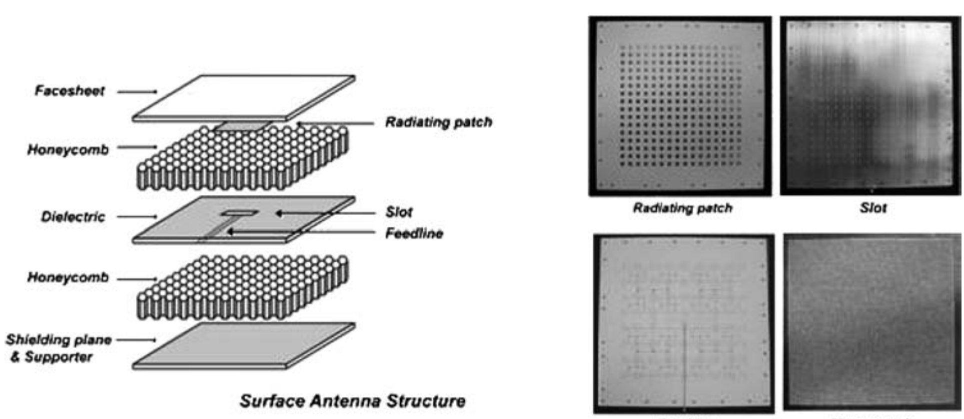
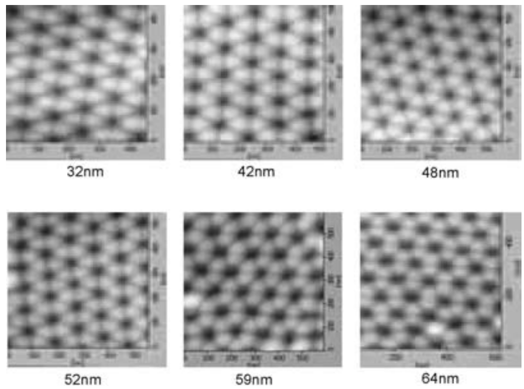
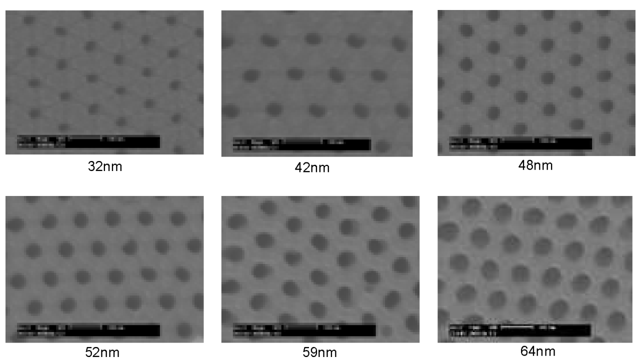


Figure 44. Surface-antenna structure for satellite communication.



(a)



(b)

Figure 45. AFM and SEM images of anodic aluminum oxide (AAO). (a) AFM image. (b) SEM image.

anodic aluminum oxide (AAO) films as nano-honeycomb structures because AAO films have certain advantageous properties, such as very high aspect ratio, self-ordered hexagonal pore structure, and simple control of pore dimensions. They also made AAO films with pore diameters from 30 to 450 nm. The mechanical and tribological properties were measured using an atomic force microscope, Nano-UTM, and Nano-Indenter, and the properties are theoretically analyzed.

2.10. Composites Interface and NDE Laboratory, GSNU

The Composites Interface and NDE Laboratory (http://nongae.gsnu.ac.kr/∼jmpark) supervised by Professor J. M. Park has been working for over twenty years on the interfacial properties of composite materials using electro-micromechanical techniques and nondestructive evaluation in composite materials as the following subtopics.

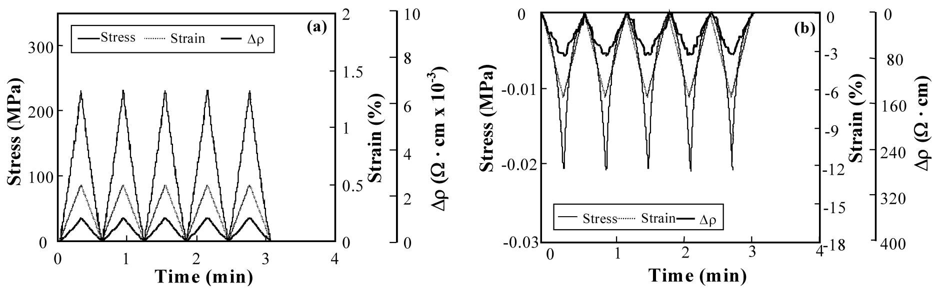


Figure 46. Loading sensing of composites using electro pull-out test under tension and compression.

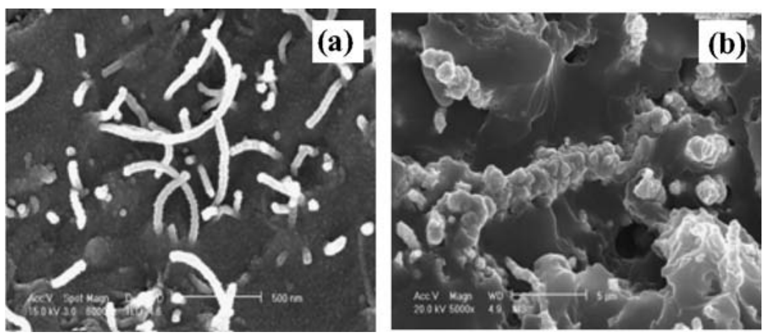


Figure 47. FE-SEM photograph of carbon nanotube and Ni nanowire strands/epoxy composites.

2.10.1. Inherent sensing and interfacial evaluation of CNT, CNF, Ni nanowire strands, Electrospun PVDF nanocomposites. For the past few years, this research group has been working on the sensing of nanocomposites using carbon nanofiber (CNF, four different aspect ratios, kindly supplied from Applied Science Inc.), carbon nanotube (CNT), Ni nanowire strand (kindly supplied from Metal Matrix Inc., Midway, Utah), and electrospun poly (vinylidene fluoride) (PVDF) for the measurement of electrical resistivity. The objective of this topic was to evaluate and to develop the multi-functional sensing materials for microfailure, tensile/compressive loading, temperature, and even humidity (Fig. 46). Now, they are planning to study the actuation of nanocomposites (Fig. 47).

2.10.2. Interfacial properties of composite materials by micromechanical technique and nondestructive evaluation (NDE). Conventional single-fiber tensile fragmentation and microdroplet tests can be used to obtain interfacial shear stress (IFSS) between any kind of fiber and matrix system. For a compressive test, the Broutman test can also be applied. As an NDE method, acoustic emission (AE) has been used as a main tool for evaluating characteristic AE events for microfailure mechanism and source location by arrival time difference from two AE sensors in composite materials. Polymeric piezoelectric PVDF, copolymer PVDF sensor and an optical fiber sensor can also be used and compared to the case of a conventional PZT AE sensor.

2.10.3. Interfacial and sensing properties of shape memory alloy (SMA) composites. Another topic studied by this group is composites containing shape memory alloys (SMAs) as an active component; this is a new class of advanced structural and functional materials. The unique properties of SMAs are due to the change of their crystalline structure which corresponds to the change of temperature or stress (Fig. 48). The superelastic behavior of SMAs exhibits the hysteresis of stress under uniform cyclic loading based on the internal molecular change between martensite and austenite (Fig. 49). SMA fiber also shows a typical transition of electrical resistance with increasing temperature.

2.10.4. Interfacial properties of natural fiber and biodegradable composites. The mechanical interface properties of natural fibers (such as hemp, jute, Ramie fibers, etc.) that were used as reinforcement with thermoplastic polypropylene and thermosetting epoxy composites have been investigated using a micromechanical test and NDE. A dynamic contact angle was used to evaluate the thermodynamic effects of adhesion and surface energies of various surface modification cases. The natural fiber composite has many advantages, such as low cost, low density,

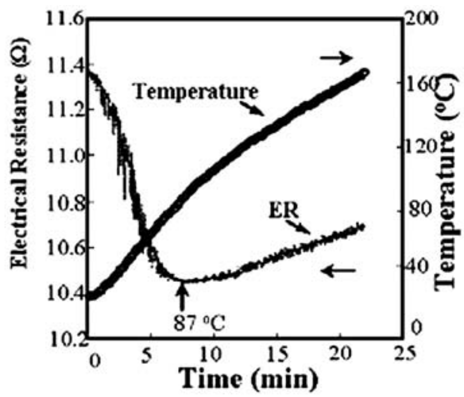


Figure 48. The change in electrical resistance of SMA fiber with changing temperature.

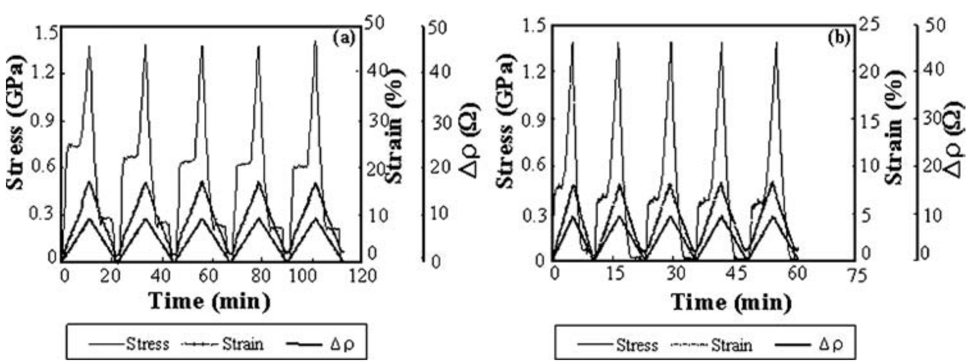


Figure 49. Cyclic test of SMA fiber and SMA/epoxy composites.

acceptable specific strength, good thermal insulation, and suitability for recycling without causing environmental damage. For medical purposes, bioabsorbable bone fixation and screw and rods can offer major advantages over conventional metallic implants. By-products of biodegradable composites are biocompatible in contrast to harmful metallic ions whereas the elastic modulus of biodegradable composites is closer to that of bone, which could minimize stress concentration near the edge of the implants. The Park group investigated interfacial degradation of bioabsorbable fiber/biodegradable PLLA composites with hydrolysis time.

3. ACTIVITIES OF KOREAN RESEARCH INSTITUTES

3.1. Composite Materials Laboratory, KIMM

3.1.1. Overview. The Composite Materials Laboratory (http://composite.kimm.re.kr) is a division of the Korea Institute of Machinery and Materials (KIMM), which was founded in 1981 by the Korean government for research and development in machinery and materials science. CML was established in 1983 and is one of the oldest laboratories in Korea investigating composite materials.

In the last decade, the composites industry in Korea has grown rapidly. The raw materials for composites, such as glass fibers, carbon fibers, high performance polymeric resins and prepregs, are produced by domestic industries. In various sectors, these high performance composite products and related research and development are in great demand.

As one of the leading research groups in Korea, CML is concentrating on research and development in composite materials, including structural analysis, tests and evaluations, and processing technology. It has a strong cooperative research network with other research groups, universities, and industries. In order to retain active cooperation with domestic and international institutions and to provide state-of-the-art technologies, CML also conducts international research programs while holding workshops and seminars.

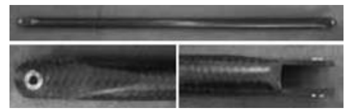
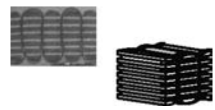
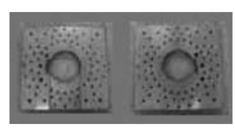
3.1.2. Personnel. There are nine regular researchers (including seven PhDs and one MS). Most of the researchers have mechanical and aerospace engineering backgrounds. This specialized area encompasses design and analysis, mechanics, manufacturing, and test and evaluation related to composite materials. There are also variable numbers of research assistants and student trainees from the local universities. They also invite foreign students or experts from overseas institutes to participate in international cooperative research programs. For the last five years there have been five long-term visiting researchers from abroad in the researcher exchange program.

3.1.3. Research areas. The research areas at CML include the liquid molding process (RTM, filament winding, pultrusion, etc.), non-liquid molding process (au-

Table 1.
Research projects

Prototypes	Contents	
Radome	– Foam cored sandwich structure (AIREX, glass/epoxy), 885 × 533 × 678 mm – Analysis of transmission efficiency using a Microwave Studio Program – Co-curing process for composites manufacturing	
Preforms for C/C Disk Brake	– 580 × 580 × 45 mm – Oxi-PAN fiber bundle and spun yarn – $[0/90]_s$ sequence, needle-punching process	
High Pressure Vessel	– Filament wound vessel (carbon/epoxy) – Service volume: 6.8, 4.0, 1.9 litres – Burst pressure: 930 bar	
Composite Wind Turbine Blade	– Large scaled blade using the modified vacuum bagging process – 750 kW grade, wind case class I (wind speed $>$52 m/s) – Length: 23.5 m, stiff skin type	
Composite propeller shaft for automobiles	– L = 2000 mm, D = 120 mm – Filament wound hybrid composite shaft (carbon, glass/epoxy) – Improved the torsional performance and NVH characteristics – Developed novel joining technology (thermal interface fitting) between composite tube and metal joints	

Table 1.
(Continued)

Prototypes	Contents	
Composite control rod for aircraft	– ∅ 32 mm × 1432 mm – Carbon/epoxy, braided preform – Vacuum-assisted resin transfer molding (VARTM) using inner pressure	
2D/3D orthogonal woven reinforced Al matrix composites	– 2D composites: carbon plain woven/Al – PC controlled pressure infiltration casting – 3D composites: carbon orthogonal woven perform/Al	
Ramp for armored vehicles	– Large and thick glass/ceramic/epoxy multi-layer composite panel – VARTM and co-curing – Structure and bulletproof hybrid type	
Transformer coil supporting plate for high speed trains	– Large and thick glass/BMI composite panel – (650 × 650 × 50 t) – High temperature resin transfer molding (RTM) – High performance at the elevated temperature	

toclave, SMC, LPMC, etc.), on-line sensing and monitoring for composites manufacturing, 7-axis fiber placement processing technology, thermoplastic composite processing, joining technology of composite materials, metal matrix composites processing, optimal design and processing of functional composite materials, textile technology (2D and 3D braiding/weaving), nanocomposites, etc.

CML possesses most of the equipment for processing, testing and evaluation necessary for composite materials and its prototypes including 7-axis fiber placement M/C, braiding M/C (2D circular, 3D rectangular), multi-layer weaving M/C, thermal test M/C (DSC, TMA) and multi-axial testing M/C. The equipment that is operated jointly with another laboratory in KIMM includes universal testing M/Cs of various capacities, image analyzer, high resolution microscope, SEM, TEM, ultrasonic C-scan system, thermal analysis system, high temperature dilatometer, conductivity meter, etc. In the Computer Simulation Laboratory, NASTRAN, NISA-II, CATIA, MARC or 3D-DEFORM are used for the structural analysis.

3.1.4. Achievements. The composites parts resulting from various representative research projects that have been conducted in the last five years are shown in Table 1.

In close cooperative research with major Korean aerospace companies, aircraft prototypes have been developed, such as aileron control tabs, ultra light aircraft structures and rotor blades for helicopters.

3.1.5. The future. In an effort to encourage technology transfer, the development of composites manufacturing technology will be concentrated by establishing cooperative research programs with industry. To meet the demand of future industries, CML is conducting research on the nanocomposites, natural fiber reinforced composites and smart composites. CML also continue to work on the basis of industry–university–research institute cooperation in large-scale national projects. One example is the New Frontier Project, in which CML takes part in the development of large composite parts utilizing liquid processing technology with the potential application of beam structures for transportation, bridge decks and ship hulls. Other large-scale researches are also performed in the National Laboratory Program, Core Technology Program and District Industrial Development Program. The Fiber Placement System will be fully utilized in the development of composite parts for aerospace applications. In this process, CML will take advantage of their expertise on the design/analysis, manufacturing, and test/evaluation on composite materials. CML is always interested in international researcher/student exchange programs, which have been intermittently conducted since 1995 with Germany, USA, and China.

3.2. Korea Aerospace Research Institute, KARI

The Korea Aerospace Research Institute (http://www.kari.re.kr) is working on the development of aircraft, artificial satellites and rockets. They also conduct type certification of aircraft and quality assurance for space products as a delegated task by the Ministry of Construction and Transportation. The ongoing aircraft development programs include the Stratospheric Airship, Next-Generation Helicopter and a Smart Unmanned Aerial Vehicle.

To reduce the weight of the flight structures, composite structures are increasingly applied to the airship and the helicopter: composite tail wings, gondola and motor mount of airship VIA 50, and composite hub and blade for the helicopter. Composite materials have also been applied to space structures: Korea Multipurpose Satellite 2 (KOMSAT-2), liquid-fueled scientific rocket KSR-III, space launch vehicle KSLV-I. Aerospace research and development in Korea progresses in accordance with ‘The Mid and Long-term National Space Development Plan’ of the Ministry of Science and Technology, and ‘The Master Plan for the Development of the Aerospace Industry’ of the Ministry of Commerce, Industry and Energy.

The mission and major functions of KARI are as follows:

– To perform basic and applied researches in aerospace technology;
– To perform government-delegated tasks and support policy development;
– To support aerospace industries and transfer technology.

There are 5 core fields of Aerospace Technology R&D in KARI as follows:

– Aeronautics;
– Space Launch Vehicle;
– Satellite/Satellite Operation Center;
– Space Center;
– Quality and Certification Center.

3.2.1. Introduction to the Aeronautics Program Office (APO). The APO is responsible for unique missions of aviation in KARI and consists of 3 divisions and 10 departments as follows. The organization of these departments is shown in Fig. 50.

The aircraft is an integrated product of design, analysis, testing and manufacturing technologies. In nature, it is an R&D-oriented synthetic technology that embraces aeronautical, structural, electrical, electronic, and materials engineering. Also, it has technology-leading characteristics that have enormous spin-off effects on other industries.

The KHP (Korean Helicopter Program) project is a large-scale national development project. The APO will develop the dual-use core components (rotor, engine, landing gear, air data system, etc.) for the KHP. In addition, the APO is developing

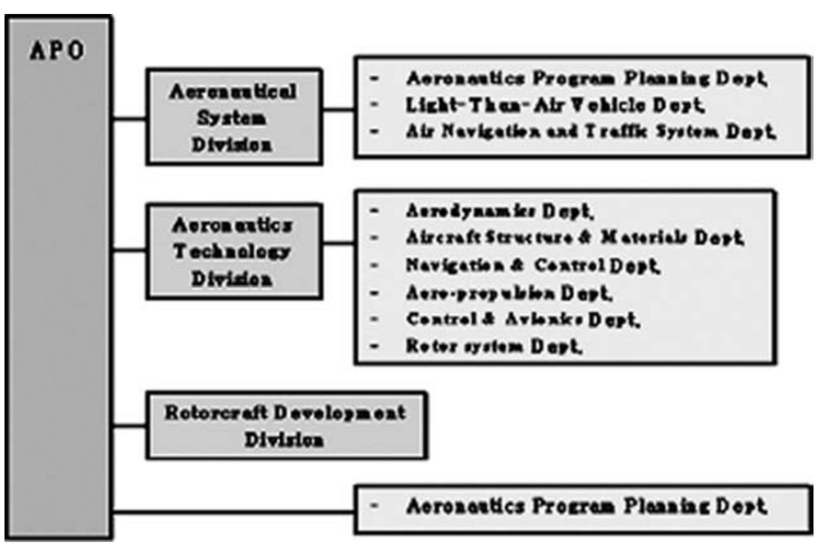


Figure 50. Aeronautics Program Office.

a canard type composite aircraft which has four seats and a single engine. As a special project, Smart UAV (tilt rotor composite aircraft) for remote investigation and surveillance is also being carried out (Fig. 51).

3.2.2. Introduction to the Aircraft Structure and Materials Department (ASMD). The ASMD leads the development of technology for design, analysis and tests in the field of aircraft structures and supports the development of aerospace vehicles under national projects. ASMD has the technology for load, stress, durability and damage tolerance, dynamic and aeroelasticity analyses. ASMD also developed test technology, such as the design development test, full-scale test, durability and damage tolerance test and integrated test equipment and expertise (Fig. 52).

ASMD has successfully carried out the structural development and structural tests for supporting national projects for the last decade as follows (Fig. 53):

- Structural design, analysis, and tests and load analysis for 8 passenger composite twin-engine aircraft;
- Design development test for Aft Fuselage BKHD of T-50;

Figure 51. KHP conceptual model, Canard type aircraft, and Smart UAV from left.

Figure 52. 8 passengers composite aircraft FEM model and wing static test.

Figure 53. DDT of T-50 Aft fuselage BKHD, KSR-III static test, T-50 full-scale static test from left.

– Structural tests of KSR(Korea Sounding Rocket)-III;

– T-50 full-scale static test.

Also, ASMD is currently performing structural development and tests as follows (Fig. 54):

– Structural design and analysis and load analysis of new concept aircraft, smart UAV;

– Structural analysis and tests and load analysis of the canard type composite aircraft;

– Structural tests of Small Satellite Launch Vehicle (KSLV-I);

– Design development tests for B787 wing tip panel.

Crash survival tests of the black box for small aircraft are being performed to support development (Fig. 55). Research on gust load alleviation is also being carried out for UAV safety improvement. The gust load alleviation technology using the control surface is being developed to reduce the response of an airplane to atmospheric turbulence. It is expected that this technology can be applied to a design of high aspect ratio and flexible wing. ASMD will start to develop a landing gear system for KHP.

The Smart UAV (unmanned air vehicle) Development Program is developing a smart UAV system which has smart abilities of intelligent avoidance of foreign objects and autonomous flight as well as high speed forward flight and VTOL (vertical take-off and landing). In July 2002, the program was selected as one of

Figure 54. Smart UAV FEM analysis, Canard type aircraft static test, KSLV-1 static test from left.

Figure 55. Black box crush test, wind tunnel test for gust load alleviation, and typical helicopter landing gear from left.

the 21st Century Frontier Research Programs funded by MOST (Ministry of Science and Technology). In order to perform the program (Fig. 56), the SUDC (Smart UAV Development Center) had been founded as an independent organization in KARI (Korea Aerospace Research Institute). For the program, more than 40 research teams and more than 370 researchers from many industrial companies including KAI (Korea Aerospace Industry) and domestic/foreign universities/institutes have participated. The first stage research plan for the preliminary design of the

Figure 56. Concept of Smart UAV.

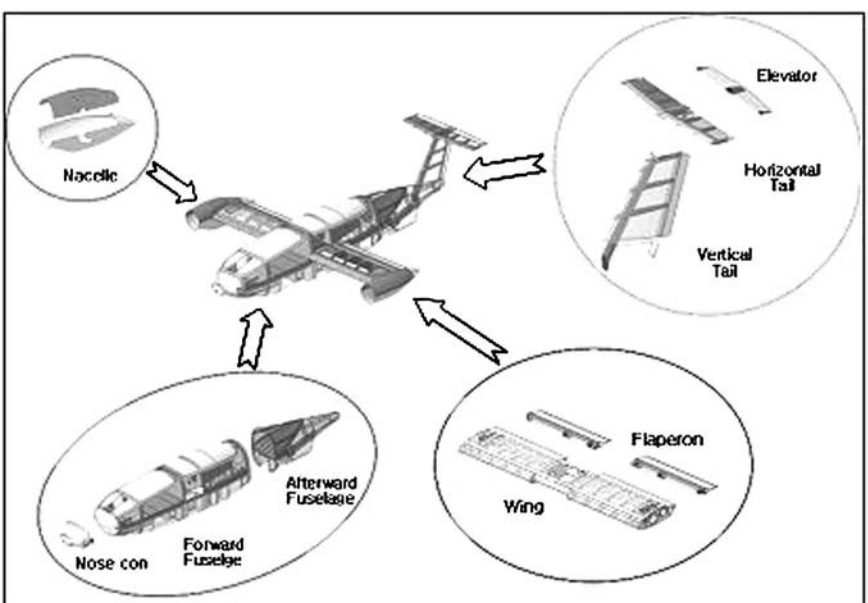


Figure 57. Adoption of composite materials in Smart UAV.

system had been finished by March 2005, and the second stage research for detail design/manufacturing/flight test will continue until March 2009. From the second stage, MOCIE (Ministry of Commerce, Industry and Energy) has been managing the program instead of MOST. It is projected that the total budget will be 140 million dollars over approximately 10 years.

In the Smart UAV Development Program, some research activities on composite materials have been carried out (Fig. 57). First, KAI and DACC have been designing most of the airframe of the aircraft using advanced composite materials, i.e. unidirectional or fabric carbon fiber reinforced composite materials satisfying DMS 2288 specification. Some of the skin structures and control surfaces, such as flaperon and elevator, will be manufactured as sandwich type structures to increase buckling resistance. Some parts of the near engine and exhaust duct will be manufactured using high temperature (about 200°C) resin, the BMI (bismaleimide) by VARTM (vacuum assisted resin transfer molding) processing technique, which will be developed by KIMM (Korea Institute of Machinery and Materials). This is the first time that the application of the VARTM processing technique for high temperature composite structures in the aerospace field has been used in Korea.

4. RESEARCH AND DEVELOPMENT IN KOREAN INDUSTRIES

4.1. Hankuk Fiber Group

Hankuk Fiber (http://www.fiber-x.com), established in 1972, has been working in the fields of composite material production and composite part manufacturing. The vertically integrated business in composites is well developed with its seven business divisions: glass fiber spinning and prepreg division, carbon fiber prepreg division, transportation part manufacturing division, glass paper production division, defence and aerospace manufacturing division, insulating panel division, and GRP pipe production division.

The glass fiber spinning and prepregging division has the capability of 15 000 tons of glass fiber production per year (Fig. 58). There are 200 weaving looms and 20 vertical wet-type and 5 hot-melt type prepregging machines.

Figure 58. Glass fiber products and glass, carbon and aramid fiber prepregs.

Figure 59. Composite parts for defence and aircraft applications.

Figure 60. Continuous filament winding process.

The carbon fiber prepreg division produces 2 000 000 sq. m/year. The major application areas are in sporting goods, construction reinforcement, and aircraft parts.

The defense and aerospace division produces various types of products to meet the customer's needs (Fig. 59). The autoclave process, RTM, VART, high press moulding and filament winding process are used. One of the autoclaves is 30 m in length and 5 m in diameter (Fig. 60). Its NDT inspection facilities, the bird-impact testing equipment, and the pressure testers are prepared to ensure the quality of the final products.

Glass fiber reinforced plastic pipes for water supply are formed of glass fiber, unsaturated polyester resin, and resin mortar. The products conform to ISO10639 and ISO10467. The continuous filament-winding machine has a high production rate and it is a cost-effective operation.

Figure 61. Korean tilting train express (TTX).

Figure 62. Static loading test for composite bodyshell.

Figure 63. Concept design for FRT project.

Composite parts for trains, buses, and ships are produced in the transportation part manufacturing division (Figs 61, 62, and 63). The quality of products meets the world's leading requirements on fire, smoke and toxicity. Consequently, the high quality of the interior panels and cap-masks has attracted world train manufacturers such as Hong Kong T.K.E. line subway. Using the newly developed phenol matrix along with the autoclave process resulted in composite parts with dimensional stability and high mechanical properties. The Korean Government supports our company's programs like the 'Tilting Train eXpress(TTX)' — a train with a composite body-shell, low-floor level bus (fuel-cell rubber-tired tram), and Wing-in-Ground projects (WIG).

The composite research institute is involved in new composite material development and improving the business divisions. As one of the best composite material

Figure 64. Autoclave for specimen preparation.

Figure 65. Bird-strike tester. DACC Co. Ltd.

organizations in Korea, the institute has various chemical analysis instruments and mechanical-testing equipments (Fig. 64).

4.2. DACC

DACC (http://www.dacc21.com/) is one of the leading companies in the field of composite structures; especially, high-temperature materials and light-structures. It began its operation in 1984 initially manufacturing aircraft composite structures ordered from the aircraft manufacturer and producing self-developing carbon–carbon brake disks and filament-wound external fuel tanks for aircraft (Fig. 65). In addition, it has achieved many advanced composite products including composite wings, high temperature carbon–carbon materials for industrial applications, defense products and so on. It continues to design and manufacture highly engineered products for aircraft and commercial use (Fig. 66).

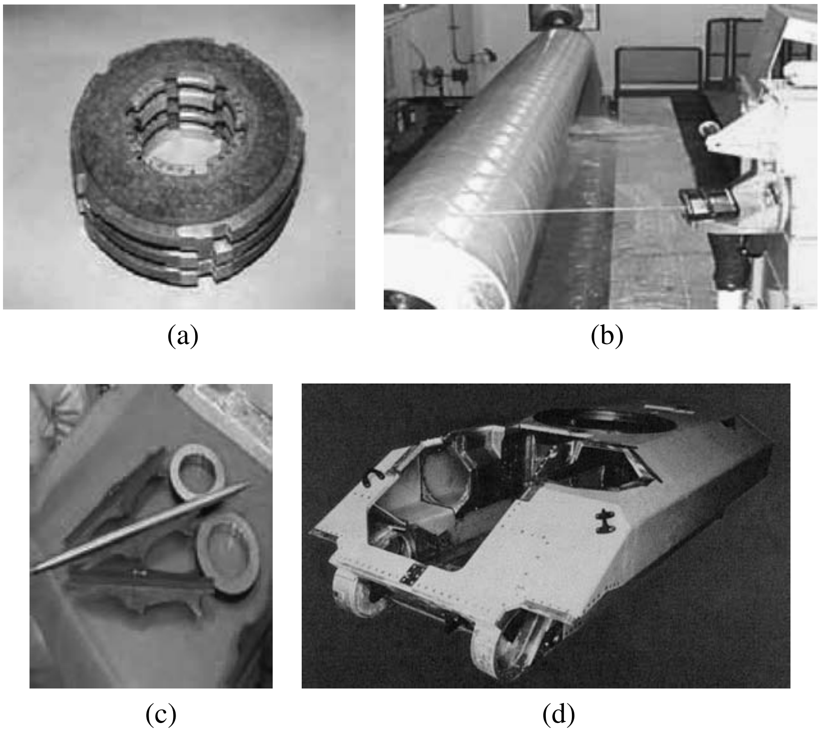


Figure 66. Major products of DACC. (a) Carbon–Carbon brake disk. (b) Launcher tube. (c) Composite sabot. (d) Composite hull.

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NOTES

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