Composite Materials

Course contents:

The subject of composite materials is truly an inter- and multidisciplinary one. People working in fields such as metallurgy and materials science and engineering, chemistry and chemical engineering, solid mechanics, and fracture mechanics have made important contributions to the field of composite materials. It would be an impossible task in the course to cover the subject from all these viewpoints. We shall restrict ourselves in this course to the objective of obtaining an understanding of composite properties (e.g., mechanical, physical, and thermal) as controlled by their structure at micro- and macro-levels. This involves a knowledge of the properties of the individual constituents that form the composite system, the role of interface between the components, the consequences of joining together, say, a fiber and matrix material to form a unit composite ply, and the consequences of joining together these unit composites or plies to form a macrocomposite, a macroscopic engineering component as per some optimum engineering specifications. Time and again, we shall be emphasizing this main theme, that is structure–property correlations at various levels that help us to understand the behavior of composites.

Subjects covered by the lectures are

- Composite Material Structure and Processing
- Mechanical Properties of Composite Materials (Modulus of Elasticity, Strength, Ductiluty)
- Effect of Damage on the Mechanical Properties
- Durability and Degradation of Materials (Corrosion Resistance, Corrosion Protection)
- Materials for Lightweight Structures, Civil Infrastructure, Joining and Repair
- Types of Composite Materials (Polymer Matrix Composite Materials, Metal Matrix Composites, Ceramic Matrix Composite, Carbon Fiber/Carbon Matrix Composites)
- Micromechanics of Composites
- Macromechanics of Composites
- Monotonic Strength and Fracture
- Fatigue and Creep
- Designing with Composites
- Nonconventional Composites

Learning outcomes of the course :

Through a deep understanding of the theory and the realization of a project, the student will be able to apply theoretical knowledge to solve composite materials problems. In particular:

- He will have a deep understanding of current challenges in the field of composite materials.
- He will have a deep understanding of the scientific concepts that guide the design of functional composites.
- He will be able to categorize composite materials in terms of their matrices and cover the composites in accordance with their matrix materials.
- He will be able to describe and characterize the basics types of composite materials, to give the regions of their applications.
- He will be able to analyze new problems relating to composite materials.

Prerequisites and co-requisites/ Recommended optional programme components :

Basic knowledge in

- Differential Equations

- Material Science
- Elasticity Theory
- Plasticity Theory
- Creep Theory
- Fracture Mechanics

Planned learning activities and teaching methods :

Exercises with professor assistance and personal project.

Mode of delivery (face-to-face ; distance-learning) :

Face-to-Face

Required readings :

- Krishan K. Chawla Composite Materials. Science and Engeneering. New York: Springer, 2013. 552 p.
- Composite Materials. A Vision for the Future. Eds.: Luigi Nicolais • Michele Meo Eva Milella. NY: Springer, 2011. 220 p.
- Deborah D. L. Chung. Composite Materials. Science and Applications. New York: Springer, 2010. 358 p.
- Ajayan P.M., Schadler L.S., Braun P.V. Nanocomposite science and technology. Wiley-VCH, Weinheim, 2003. pp 122–138.
- Principles of Composite Material Mechanics. CRC Press, 2011. 683 p.
- Barbero E.J. Finite Element Analysis of Composite Materials using ABAQUS. CRC Press, 2013. 444 p.

Assessment methods and criteria :

Evaluation is based on the realization of a project related to the use / development of theoretical work specific to composite materials and on an examination.
The examination is based on the whole content of the class. Problems similar to the ones studied during the classes, and new problems will be part of the questions. Justification using the theoretical content is also asked.
Participation to the examination and achievement of the project are mandatory.

Teaching Method: Class participation is mandatory. Everyone is expected to participate in discussions relating to reading materials, homework, exams and lectures.

Guaranteed Recipe for Success:
1) Take notes during lecture and sections.
2) After each lecture but before the next lecture review your notes. Identify the parts you do not understand.
3) Come to each lecture and discussion section with specific questions.
4) Keep up with the reading so that you have some familiarity with each topic prior to hearing about it in the lecture.
5) Find at least one "partner" in the class with whom you can meet at least once or twice a week to discuss materials from the lectures, the reading assignments and the homework.
6) Take the homework assignment seriously. Do not try to do the whole assignment the night before it is due. Some version of the homework questions will appear on the exams.

Composite Materials
Course Contents

15.1 Nanocomposites
15.1.1 Polymer Clay Nanocomposites
15.2 Self-Healing Composites
15.3 Self-Reinforced Composites
15.4 Biocomposites
15.5 Laminates
15.5.1 Ceramic Laminates
15.5.2 Hybrid Composites

Further Reading

1. Lee JJ et al (2001) Historical and future trends in aircraft performance, cost, and emissions. J Annu Rev Energy Environ 26:167–200. doi:10.1146/annurev.energy.26.1.167.
2. Dijkstra HS (2008) Materials for future aircraft structures. MSc Ph.D. thesis, Faculty of Aerospace Engineering, Delft University of Technology, The Netherlands.
3. Adams DF, Carlsson LA, Pipes RB (1998) Experimental characterization of advanced composite materials, 3rd edn. CRC, Boca Raton, FL.
4. Kelly A, Mileiko ST (eds) (1983) Fabrication of composites. North-Holland, Amsterdam.
5. Vaidya U (2011) Composites for automotive, truck and mass transit. DEStech Pub, Lancaster, PA.
6. Chawla N, Chawla KK (2006) Metal matrix composites. Springer, New York.
7. Clyne TW, Withers PJ (1993) An introduction to metal matrix composites. Cambridge University Press, Cambridge.
8. Daniel IM, Ishai O (2006) Engineering mechanics of composite materials, 2nd edn. Oxford University Press, New York.
9. Bunsell AR, Renard J (2005) Fundamentals of fibre reinforced composites. Institute of Physics Pub, Bristol.
10. Talreja R (ed) (1994) Damage mechanics of composite materials. Elsevier, Amsterdam.

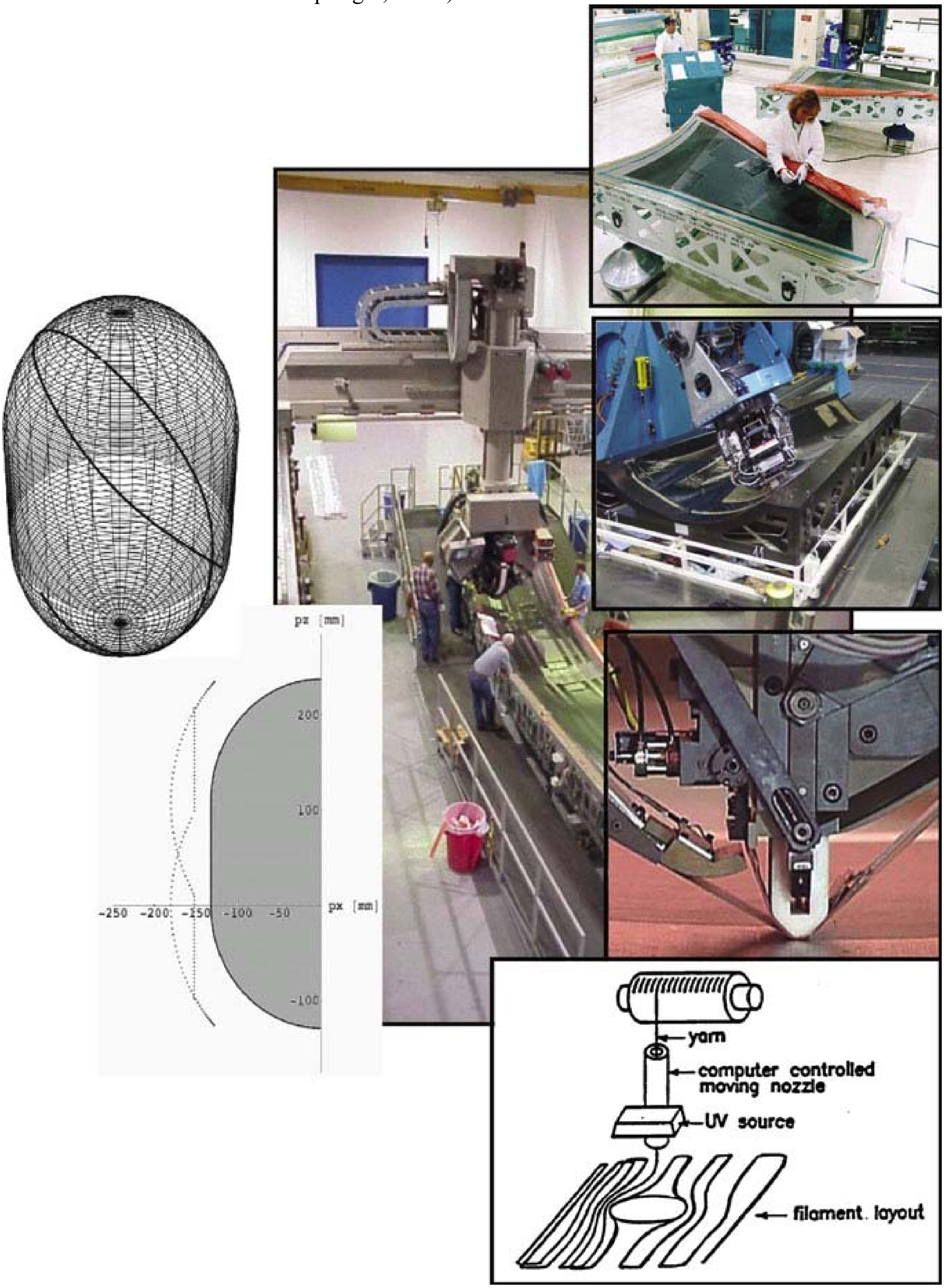
EXAMPLES

Consider the sandwich concept used in aviation (Composite Materials. A Vision for the Future. Eds.: Luigi Nicolais • Michele Meo Eva Milella. NY: Springer, 2011.)

A carbon/carbon brake assembly that is used on a Boeing 767 airplane

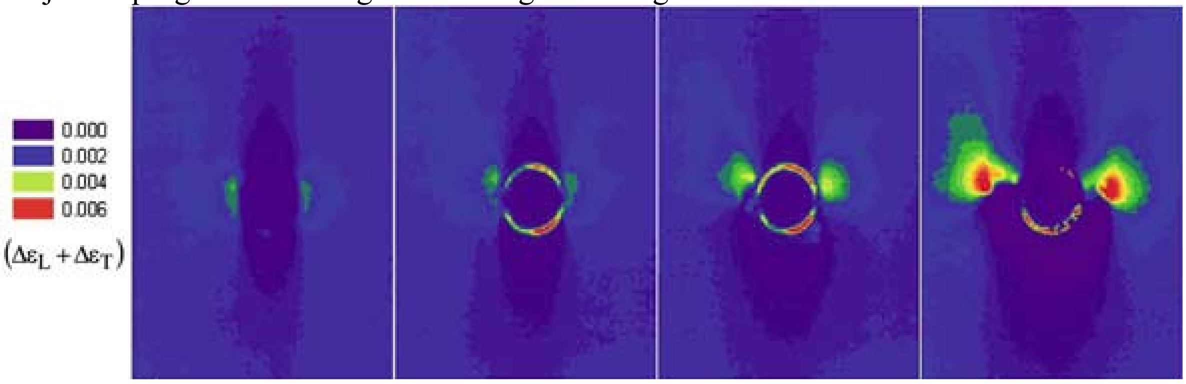
Consider the illustrations.

Pre-impregnated fibres, tows and tapes have a breakthrough thanks to the availability of capital-intensive fibre-placement robots, changing aircraft structures manufacturing into an industrial and labour extensive activity. (Composite Materials. A Vision for the Future. Eds.: Luigi Nicolais • Michele Meo Eva Milella. NY: Springer, 2011.)



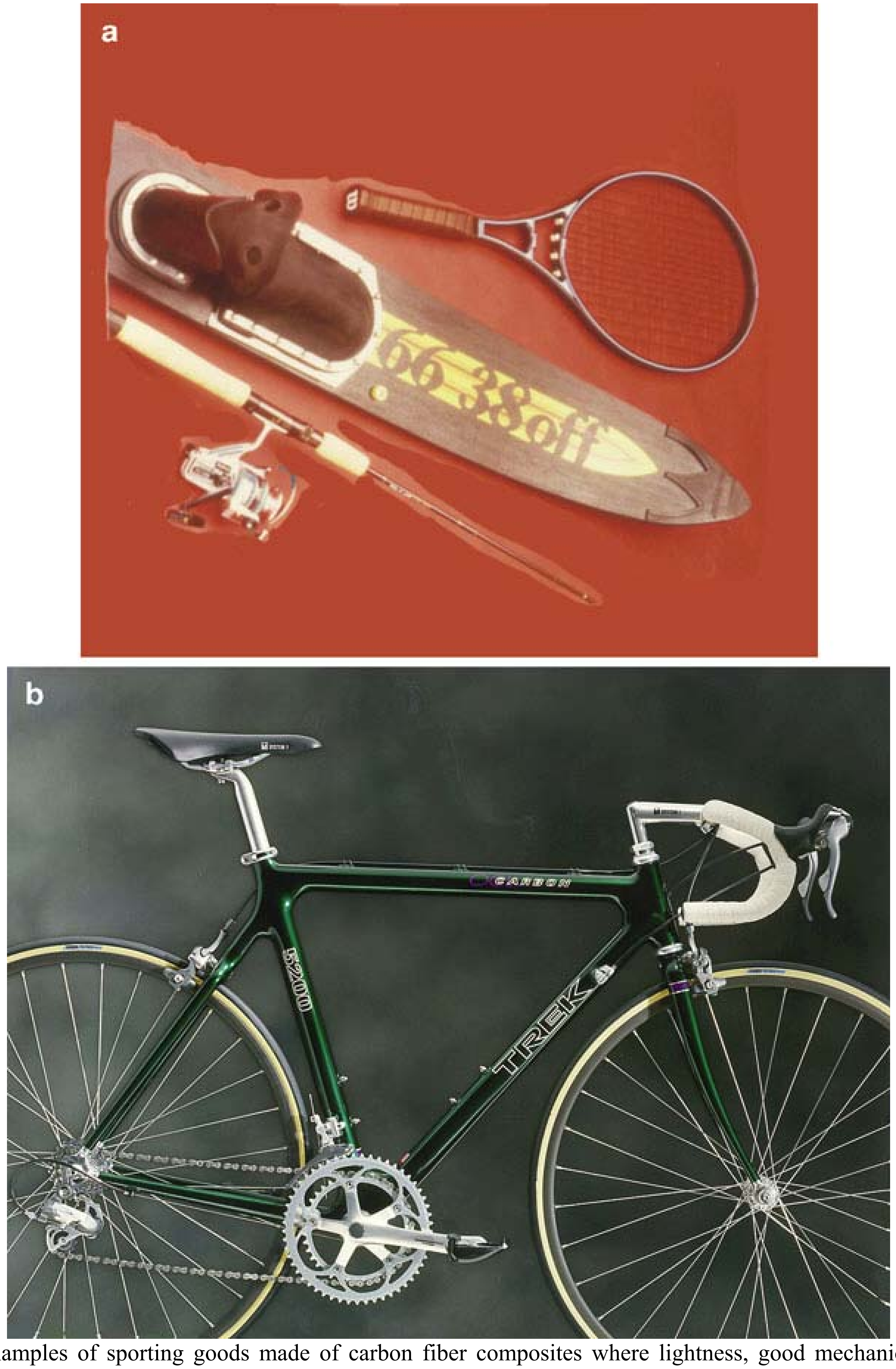
Industrial manufacturing the faster the better reduce mass of rotating mandrels reduce mass of head place dry fibres keep them straight, simple geodetics

Damage progression around a circular hole. Figure shows maps of the principal strains around a central circular hole in a glass epoxy plate obtained using thermoelastic stress analysis (TSA) subject to progressive damage under fatigue loading

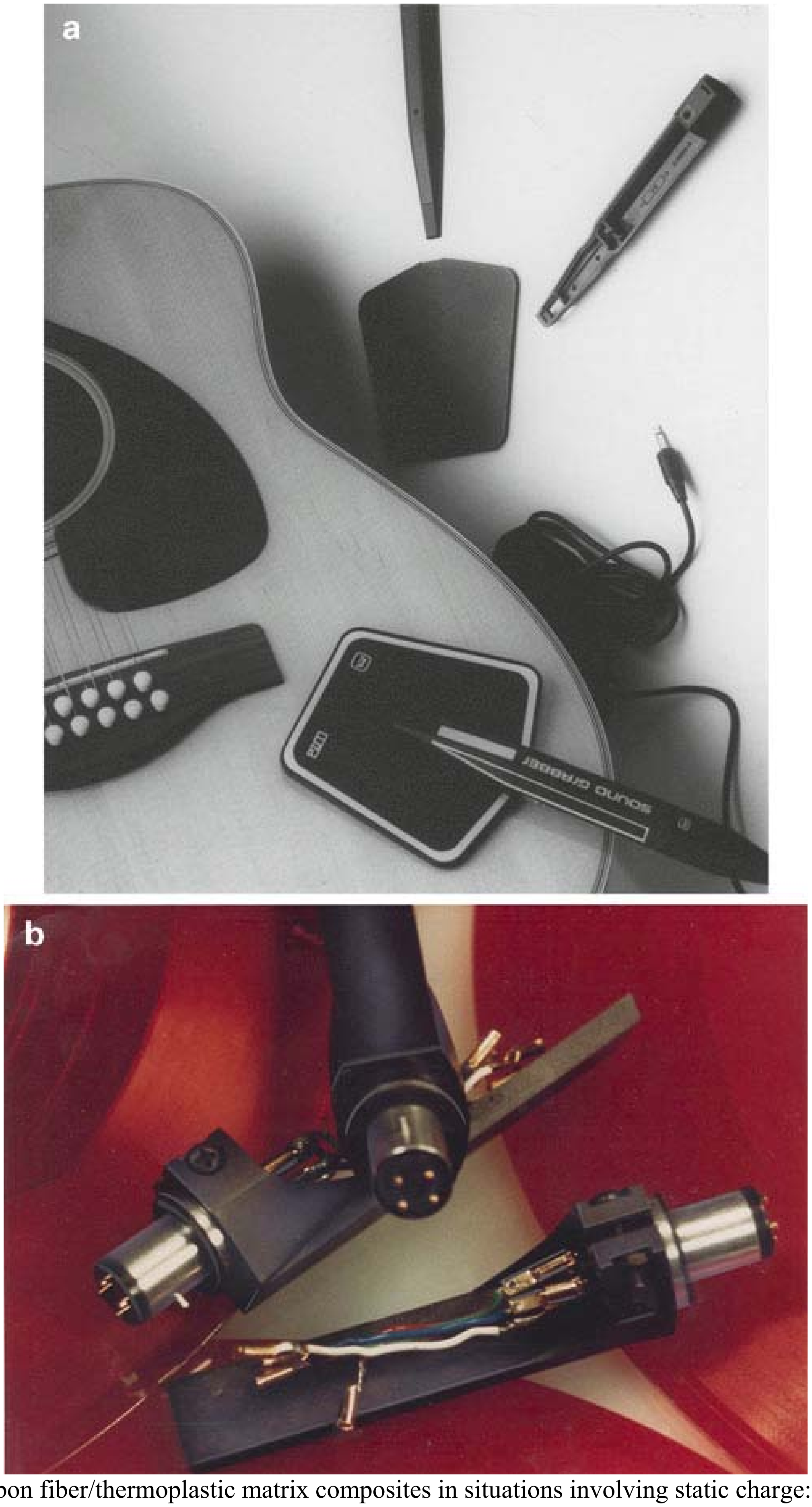


Consider the structures

Blades of GEnx engine are made of carbon fiber/epoxy composites **(**Krishan K. Chawla Composite Materials. Science and Engeneering. New York: Springer, 2013. 552 p.**)**



Examples of sporting goods made of carbon fiber composites where lightness, good mechanical characteristics, and sleek lines make the items very attractive: (a) tennis racket, a pair of skis, and a fishing rod **(**Krishan K. Chawla Composite Materials. Science and Engeneering. New York: Springer, 2013. 552 p.**)**



Use of carbon fiber/thermoplastic matrix composites in situations involving static charge: (a) microphone, (b) a head shell unit of a turntable arm **(**Krishan K. Chawla Composite Materials. Science and Engeneering. New York: Springer, 2013. 552 p.**)**

An offshore wind farm at Middelgrunden near Copenhagen, Denmark. Each rotor blade is 36.8 m long.

Problems (Krishan K. Chawla Composite Materials. Science and Engeneering. New York: Springer, 2013. 552 p.**)**

Reinforcements

1.1. Describe the structure and properties of some fiber reinforced composites that occur in nature.
1.2. Many ceramic-based composite materials are used in the electronics industry. Describe some of these electroceramic composites.
1.3. Describe the use of composite materials in the Voyager airplane that circled the globe for the first time without refueling in flight.
1.4. Nail is a fibrous composite. Describe its components, microstructure, and properties.
1.5. Discuss the use of composite materials in civilian aircraft, with special attention to Boeing 787 and Airbus A380 aircraft.

2.1. Nonwoven fibrous mats can be formed through entanglement and/or fibers bonded in the form of webs or yarns by chemical or mechanical means. What are the advantages and disadvantages of such nonwovens over similar woven mats?
2.2. Glass fibers are complex mixtures of silicates and borosilicates containing mixed sodium, potassium, calcium, magnesium, and other oxides. Such a glass fiber can be regarded as an inorganic polymeric fiber. Do you think you can
provide the chemical structure of such a inorganic fiber chain?
2.3. A special kind of glass fiber is used as a medium for the transmission of light signals. Discuss the specific requirements for such an optical fiber.
2.4. The compressive strength of aramid fiber is about one-eighth of its tensile stress. Estimate the smallest diameter of a rod on which the aramid fiber can be wound without causing kinks, etc., on its compression side.
2.5. Several types of Kevlar aramid fibers are available commercially. Draw schematically the stress–strain curves of Kevlar 49 and Kevlar 29. Describe how much of the strain is elastic (linear or nonlinear). What microstructural processes occur during their deformation?

2.6. Aramid fiber, when fractured in tension, shows characteristically longitudinal splitting, i.e., microfibrillation is observed. Explain why.
2.7. Describe the structural differences between Kevlar and Nomex (both aramids) that are responsible for their different mechanical characteristics.
2.8. What is asbestos fiber and why is it considered to be a health hazard?
2.9. Describe the problems involved in mechanical testing of short fibers such as whiskers.

Matrix Materials

3.1. Ductility, the ability to deform plastically in response to stresses, is more of a characteristic of metals than it is of ceramics or polymers. Why?
3.2. Ceramic materials generally have some residual porosity. How does the presence of porosity affect the elastic constants of ceramic materials? How does it affect the fracture energy of ceramics?
3.3. Explain why it is difficult to compare the stress–strain behavior of polymers (particularly thermoplastics) with that of metals.
3.4. The mechanical behavior of a polymer can be represented by an elastic spring and a dashpot in parallel (Voigt model). For such a model we can write for stress

$$\sigma = \sigma_{el} + \sigma_{visc} = E\varepsilon + \eta \frac{d\varepsilon}{dt}$$

where E is the Young's modulus, e is the strain, _ is the viscosity, and t is the time. Show that

$$\varepsilon = \frac{\sigma}{E}\left[1 - \exp\left(-\frac{E}{\eta}t\right)\right]$$

3.5. What is the effect of the degree of crystallinity on fatigue resistance of polymers?
3.6. Discuss the importance of thermal effects (hysteretic heating) on fatigue of polymers.
3.7. Glass-ceramics combine the generally superior mechanical properties of crystalline ceramics with the processing ease of glasses. Give a typical thermal cycle involving the various stages for producing a glass-ceramic.
3.8. Silica-based glasses and many polymers have amorphous structure. An amorphous structure is characterized by a glass transition temperature. Explain why silica-based glasses have a much higher glass transition temperature than polymers.

Interfaces

4.1. Describe some techniques for measuring interfacial energies in different composite systems.
4.2. In order to study the interfacial reactions between the fiber and matrix, oftentimes one uses very high temperatures in order to reduce the time necessary for the experiment. What are the objections to such accelerated tests?
4.3. What are the objections to the use of short beam shear test to measure the interlaminar shear strength (ILSS)?
4.4. Diffusion along free surface is faster than in the bulk of a material. Similarly, diffusion along a grain boundary is faster than in the lattice. Taking these factors into account, write an expression for diffusion coefficients in order of descent for diffusion along lattice, dislocation, grain boundary, reinforcement/ matrix interface, and surface. Explain the reason behind your answer.
4.5. Discuss the importance of moisture diffusion in fiber reinforced polymer matrix composites. Recall that moisture absorption in PMCs is largely due to the permeability of the polymer matrix. Suggest some possible effects of moisture absorption in fiber reinforced PMCs in terms of effects on different moduli (along the fiber and perpendicular to the fiber) and ILSS.

5 Polymer Matrix Composites

5.1. Why are prepregs so important in polymer matrix composites? What are their advantages? Describe the different types of prepregs.
5.2. Randomly distributed short fibers should result in more or less isotropic properties in an injection molded composite. But this is generally not true. Why? What are the other limitations of injection molding process?

5.3. In a thermally cured PMC, the fiber surface treatments have been well established for certain systems. For example, silanes are used on glass fiber in an epoxy matrix while an oxidizing treatment to carbon fiber for use in an epoxy matrix. What would be the effect of electron beam curing on the interface development in a PMC?
5.4. Describe the major differences in the processing of composites having a thermoset matrix and those having a thermoplastic matrix.
5.5. What are the important factors in regard to fire resistance of PMCs?

6 Metal Matrix Composites
6.1. Pressure casting is frequently used to prepare metal matrix composite. Explain why.
6.2. Describe some of the advantages of metal matrix composites over monolithic metals.
6.3. Discuss the advantages of metal matrix composites vis a` vis polymer matrix composite.
6.4. Discuss the advantages and disadvantages of liquid metal processing vis a` vis other methods of fabricating metal matrix composites.
6.5. Silicon carbide (0.1 mm thick) coated boron fiber was used to reinforce a metallic matrix. The SiC coating serves as a diffusion barrier coating. Estimate the time for dissolution of this coating at 700 K if the diffusion coefficient at 700 K is 10_16 m2/s.
6.6. The metallic matrix will generally undergo constrained plastic flow in the presence of a moderately high volume fraction of high modulus fibers. Draw schematically the stress–strain curves of a constrained metal matrix (i.e., in situ behavior) and an unconstrained metal (i.e., 100% matrix metal). Explain the difference.
6.7. Aluminum and magnesium are two common metal matrix materials. What is the viscosity of molten aluminum and magnesium?
6.8. What is the effect on viscosity of adding ceramic particles to a molten metal such as aluminum or magnesium? Discuss its implications in the processing of MMCs with respect to features such as particle size, volume fraction, etc.
6.9. Discuss the problem of thermal stability of unidirectionally solidified eutectic (in situ) metallic composites.
6.10. Discuss the use of silicon carbide particle reinforced aluminum composites in braking applications.
7.Ceramic Matrix Composites
7.1. What are the sources of fiber degradation during processing of ceramic matrix composites?
7.2. Describe the advantages of using sol–gel and polymer pyrolysis techniques to process the ceramic matrix in CMCs.
7.3. Explain how a carbon fiber reinforced glass–ceramic composite can be obtained with an almost zero in-plane coefficient of thermal expansion.
7.4. Chemically, what is an alkoxide? Describe some of the alkoxides that can be used to obtain different ceramic matrixes in CMC.
7.5. Distinguish between interphase and interface.
7.6. Why is thermal shock resistance more of a problem in CMCs than in MMCs?

8. Carbon Fiber/Carbon Matrix Composites
8.1. The terms voids and cracks are frequently used interchangeably but in reality they are not synonymous. Specifically, in regard to C/C composites, distinguish between voids and microcracks in terms of their form and origin.
8.2. TEOS is often used as a glass forming sealant to heal the microcracks in C/C composites. However, there are some limitations on efficiency. Explain what the limitations are and why.
8.3. Invariably C/C composites will need to be joined to other conventional materials. Describe the different joining approaches that can be used to accomplish this; give the pros and cons of each technique.
8.4. C/C composites are frequently made of carbon fibers woven in more than three directions. What effect does this have on crack propagation, fracture surface appearance, and toughness of C/C composite?

8.5. Glass-forming sealants help close the crack-like defects in C/C composites. Are there any deleterious effects of such sealants?
8.6. Describe the NASA's Columbia shuttle disaster in which all seven astronauts lost their lives in 2003. Highlight the role of carbon/carbon composites in this disaster. How and why did the disaster occur? Describe the modifications instituted by NASA to prevent such a disaster in the future.

9. Multifilamentary Superconducting Composites
9.1. There are many known superconducting A15 compounds. Of these Nb3Al, Nb3Ga, and Nb3Ge have higher values of Tc and Hc2 than do Nb3Sn and V3Ga. How then does one explain the fact that only Nb3Sn and to a lesser extent V3Ga are available commercially?
9.2. It is believed that grain boundaries are the imperfections responsible for the flux-pinning in high-Jc materials like Nb3Sn and V3Ga. How does Jc vary with grain size?
9.3. What is the effect of any excess unreacted bronze leftover in the manufacture of Nb3Sn superconductor composite via the bronze route?
9.4. Examine the Nb–Sn phase diagram. At what temperature does the A15 compound (Nb3Sn) become unstable? Nb3Sn is formed by solid state diffusion in Nb/Cu–Sn composites at 700 _C or below. Is this in accord with information from the phase diagram? Explain.
9.5. Do you think it is important to study the effect of irradiation on superconducting materials? Why?
9.6. In the high magnetic field coils of large dimensions, rather large tensile and compressive loads can be encountered during energizing and deenergizing. Discuss the effects of cyclic stress on the superconducting coil materials.
9.7. Superconducting composites in large magnets can be subjected to high mechanical loads. Describe the sources of such loadings.

10. Micromechanics of Composites
10.1. Describe some experimental methods of measuring void content in composites. Give the limitations of each method.
10.2. Consider a 40 % Vf SiC whisker-reinforced aluminum composite. Ef j 400 GPa, Em j 70 GPa, and (l/d) j 20. Compute the longitudinal elastic modulus of this composite if all the whiskers are aligned in the longitudinal direction. Use Halpin-Tsai-Kardos equations. Take x j 2(l/d).
10.3. A composite has 40 % Vf of a 150 mm diameter fiber. The fiber strength is 2 GPa, the matrix strength is 75 MPa, while the fiber/matrix interfacial strength is 50 MPa. Assuming a linear build up of stress from the two ends of a fiber, estimate the composite strength for (a) 200 mm long fibers and (b) 3 mm long fibers.
10.4. Derive the load transfer expression using the boundary conditions. Find the average tensile stress in the fiber.
10.5. Consider a fiber reinforced composite system in which the fiber has an aspect ratio of 1,000. Estimate the minimum interfacial shear strength ti, as a percentage of the tensile stress in fiber, sf, which is necessary to avoid interface failure in the composite.
10.6. Consider an alumina fiber reinforced magnesium composite. Calculate the composite stress at the matrix yield strain. The matrix yield stress 180 MPa, Em j 70 GPa, and n j 0.3. Take Vf j 50 %.
10.7. Estimate the aspect ratio and the critical aspect ratio for aligned SiC whiskers (5 mm diameter and 2 mm long) in an aluminum alloy matrix. Assume that the matrix alloy does not show much work hardening.
10.8. Alumina whiskers (density j 3.8 g/cm3) are incorporated in a resin matrix (density j 1.3 g/cm3). What is the density of the composite? Take Vf j 0.35. What is the relative mass of the whiskers?
10.9. Consider a composite made of aligned, continuous boron fibers in an aluminum matrix. Compute the elastic moduli, parallel, and transverse to the fibers. Take Vf j 0.50.
10.10. Fractographic observations on a fiber composite showed that the average fiber pullout length was 0.5 mm. If Vfu j 1 GPa and the fiber diameter is 100 mm, calculate the strength of the interface in shear.
10.11. Consider a tungsten/copper composite with following characteristics: fiber fracture strength j 3 GPa, fiber diameter j 200 mm, and the matrix shear yield strength j 80 MPa. Estimate the critical

fiber length which will make it possible that the maximum load bearing capacity of the fiber is utilized.

11. Macromechanics of Composites

11.1. An isotropic material is subjected to a uniaxial stress. Is the stain state also uniaxial? Write the stress and strain in matrix form.
11.2. For a symmetric laminated composite, the moduli are even functions of thickness z. Starting from this definition, split the integral and show that Bij is identically zero for a symmetric laminate.
11.3. An orthotropic lamina has the following characteristics: E11=210 GPa, E22=8 GPa, G12=5 GPa, and $\nu_{12} = 0.3$. Consider a three-ply laminate made of such laminae arranged at $\theta = \pm 60^\circ$. Compute the submatrices [A], [B], and [D]. Take the ply thickness to be 1 mm.
11.4. Enumerate the various phenomena which can cause microcracking in a fiber composite.

12. Fatigue and creep

12.1. List some of the possible fatigue crack initiating sites in particle, short fiber, and continuous fiber reinforced composites.
12.2. What factors do you think will be important in the environmental effects on the fatigue behavior of fiber reinforced composites?
12.3. Discuss the effects of frequency of cycling in regard to hysteretic heating in PMCs and CMCs.
12.4. Discuss the fatigue behavior an aramid fiber reinforced PMC is subjected to fatigue at negative and positive stress ratio (R).
12.5. Which one will have a better creep resistance in air: an oxide/oxide composite or a nonoxide/nonoxide system? Explain your answer.
12.6. Diffusional creep involving mass transport becomes important at low stresses and high temperatures. Discuss the importance of reinforcement/matrix interface in creep of a composite under these conditions.
12.7. Assume that the creep of fiber and matrix can be described by a power-law and that a well bonded interface exists. Assume also that the strain rate of the composite is given be the volume weighted average of the strain rates of the fiber and matrix. Derive an expression for the strength of such a composite.
12.8. In some composites, residual thermal stress distribution obtained at room temperature on cooling from the high processing temperature results in compressive radial gripping at the interface. Discuss the effect of high temperatures or creep in such a composite.

Review Questions
1. What is meant by damping such that the damping ratio is equal to 1?
2. What is the difference between plastic viscosity and apparent viscosity?
3. What is the cause of double yielding in a carbon black paste?
4. What is the effect of antioxidants on the viscoelastic behavior of a carbon black paste?
5. Why is the addition of carbon nanofiber to the interlaminar interface of a carbon fiber (continuous) polymer-matrix composite able to enhance the vibration damping ability of the composite?
6. Why are the steel rebars used to reinforce concrete typically placed on the tension side of a concrete beam?

Review Questions
1. Why does corrosion tend to occur mainly at the crack in a piece of steel?
2. What are the anodic and cathodic reactions for the corrosion of steel in air?
3. Why is cathodic protection an expensive method of corrosion protection?
4. Why does sand blasting help toimprove the corrosionresistance of steel rebars?
5. Why does the addition of silica fume as an admixture in concrete help to improve the corrosion resistance of steel rebars embedded in the concrete?

6. What is the main advantage of a polymer of high crystallinity compared to one of low crystallinity?
7. Why is aluminumfoil quite temperature resistant, meaning that it can be used in cooking?
8. Why is the heat-affected zone in welding a problem?
9. Why does the time spent below the melting temperature prior to bonding
affect the quality of the bond for PPS?
10. What is the main advantage of using carbon fiber as a filler in an active brazing alloy?
11. What is the main advantage of using acid phosphate rather than colloidal silica as a binder?
12. Why does corrosion tend to occur in a fastened metal joint?

Review Questions

1. Why do the microcapsules of monomer used in self-healing need to be sufficiently small?
2. What is the difference between solid-state sintering and liquid-state sintering?
3. In relation to powder metallurgy, what is the advantage of the coated filler method over the admixture method?
4. What is the difference between diffusive adhesion and dispersive adhesion?
5. What is the advantage of using acid phosphate binder rather than colloidal alumina binder when making a porous article of discontinuous alumina fiber?

Review Questions

1. What is special about the behavior of the alloy known as Invar?
2. What is the difference between the admixture method and the coatedfiller method of power metallurgy?
3. Why is it undesirable to have an excessively strong bond between the fiber and the matrix in a composite with a brittle matrix?
4. Describe a method of improving the thermal conductivity of a boron nitride particle epoxy-matrix composite.
5. Describe a method for coating a carbon–carbon composite with silicon carbide.
6. What is the advantage of having silica fume, which is used as an admixture in cement, coated with silane?
7. What is the advantage of adding methylcellulose to cement?
8. What is attractive about having a high degree of graphitization in the carbon matrix of a carbon-matrix composite?

Literature and Recommendations

1. Principles of Composite Material Mechanics. CRC Press, 2011. 683 p.

The book presents a unique blend of classical and contemporary mechanics of composites technologies. While continuing to cover classical methods, this edition also includes frequent references to current state-of-the-art composites technology and research findings. Easily accessible to students, this popular bestseller incorporates the most worked-out example problems and exercises of any available textbook on mechanics of composite materials. It offers a rich, comprehensive, and up-to-date foundation for students to begin their work in composite materials science and engineering. A solutions manual and PowerPoint presentations are available for qualifying instructors.

2. Barbero E.J. Finite Element Analysis of Composite Materials using ABAQUS. CRC Press, 2013. 444 p.

Developed from the author’s graduate-level course on advanced mechanics of composite materials**, Finite Element Analysis of Composite Materials with Abaqus** shows how powerful finite element tools address practical problems in the structural analysis of composites. Unlike other texts, this one takes the theory to a hands-on level by actually solving problems. It explains the concepts involved in the detailed analysis of composites, the mechanics needed to translate those concepts into a mathematical representation of the physical reality, and the solution of the resulting boundary value problems using the commercial finite element analysis software Abaqus. The first seven chapters provide material ideal for a one-semester course. Along with offering an introduction to finite element analysis for readers without prior knowledge of the finite element method (FEM), these chapters cover the elasticity and strength of laminates, buckling analysis, free edge stresses, computational micromechanics, and viscoelastic models and composites. Emphasizing hereditary phenomena, the book goes on to discuss continuum and discrete damage mechanics as well as delaminations. More than 50 fully developed examples are interspersed with the theory, more than 75 exercises are included at the end of each chapter, and more than 50 separate pieces of Abaqus pseudocode illustrate the solution of example problems. The author’s website offers the relevant Abaqus and MATLAB® model files available for download, enabling readers to easily reproduce the examples and complete the exercises. The text also shows readers how to extend the capabilities of Abaqus via "user subroutines" and Python scripting.