9. COMPOSITES

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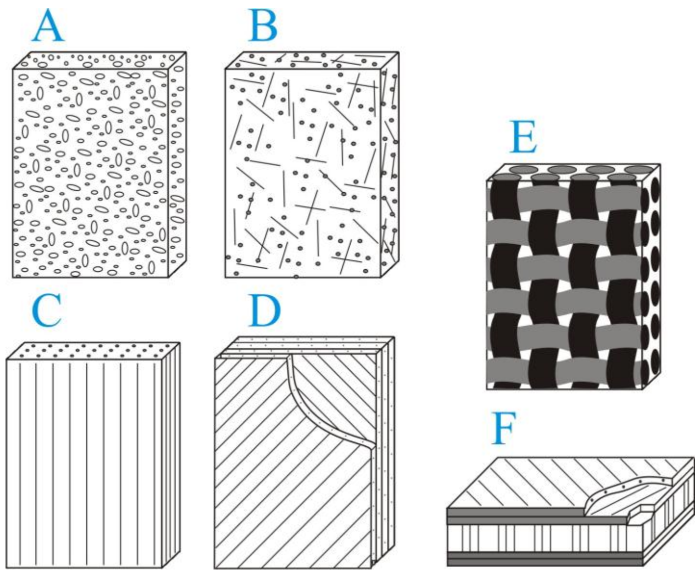
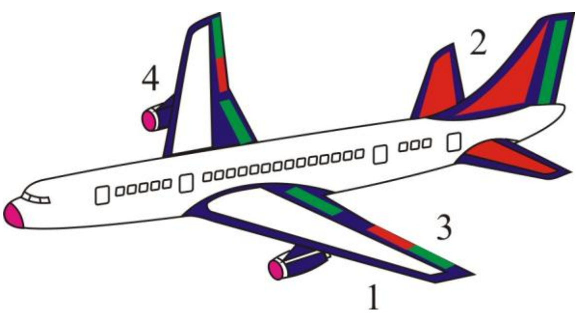
9.1 STRUCTURE OF COMPOSITES

A composite material consists of two or more components. The components have different mechanical properties.

There are the following types of composites:
A. composites reinforced by particles;
B. composites reinforced by chopped strands;
C. unidirectional composites;
D. laminates;
E. fabric reinforced plastics;
F. honeycomb composite structure;

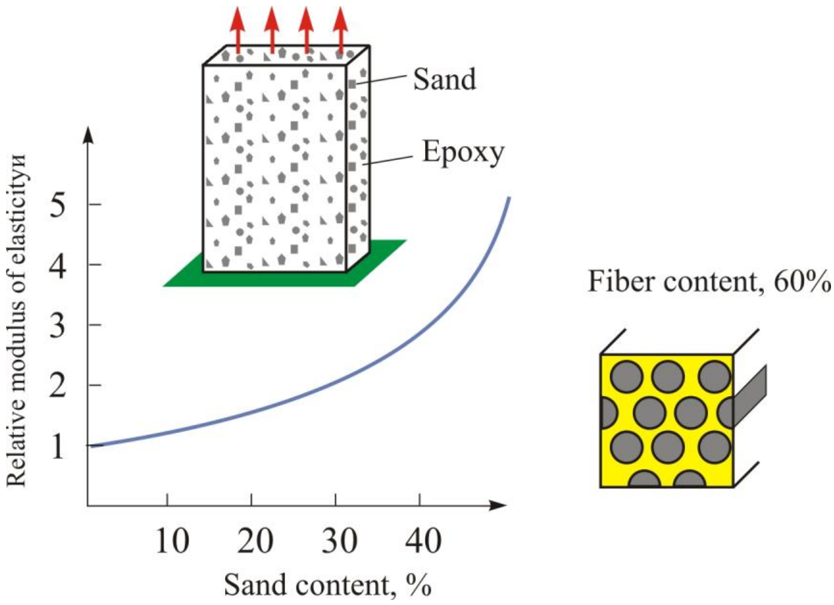


Composite materials are widely used in aerospace structures, passenger airplanes, cars, and sporting goods. The use of aramid fiber reinforced plastics (1), carbon fiber reinforced plastics (2), hybrid fiber (aramid + carbon) reinforced plastics (3), and glass fiber reinforced plastics (4) decreases the weight of passenger airplanes.

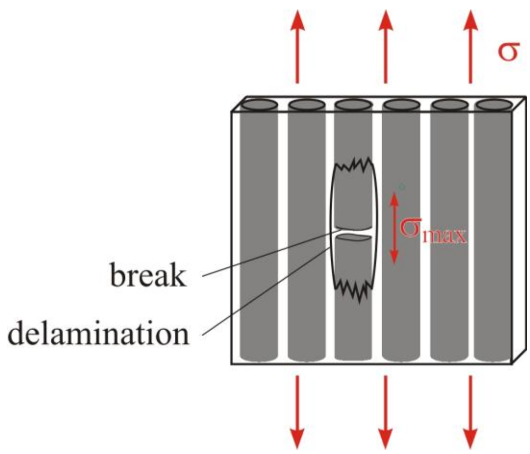


Particle content is defined by studying the cross-section of a specimen. The parameter is equal to the ratio of the total area of the particles (fibers) to the cross-sectional area of the specimen.

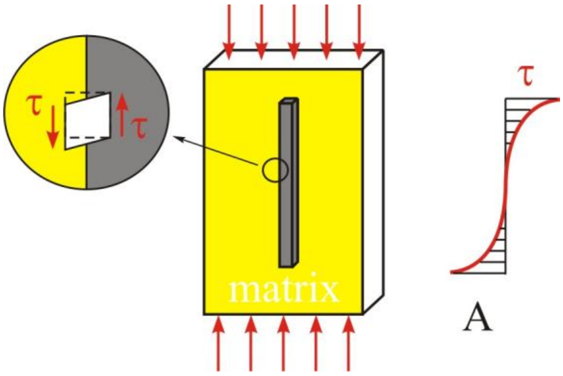
Regarding particle and fiber reinforced matrices, the modulus of elasticity will increase with larger hard particle content.



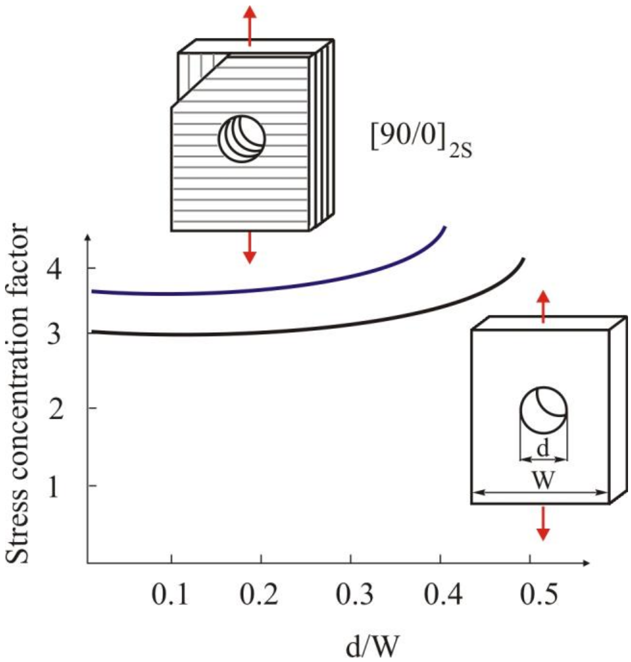
Broken rigid fibers in a flexible matrix cause stress concentration in the neighboring fibers. The stress concentration factor increases as the difference between the modulus of elasticity of the matrix and fiber increases. It can range from 1.2 to 1.5.



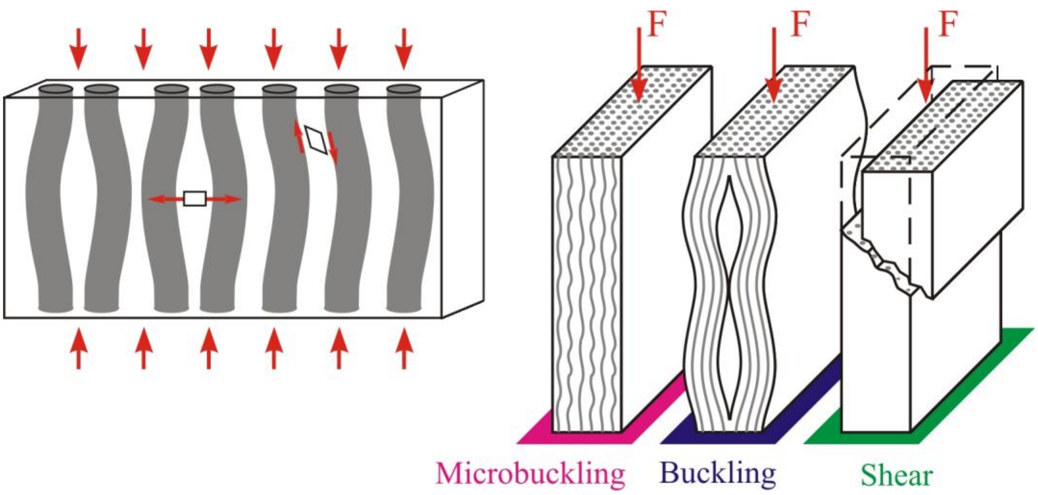
There is shear stress concentration at the bond surface between components. Stress concentration in laminate materials is higher than in isotropic materials. Thus, the strength of a notched composite specimen is rather high.



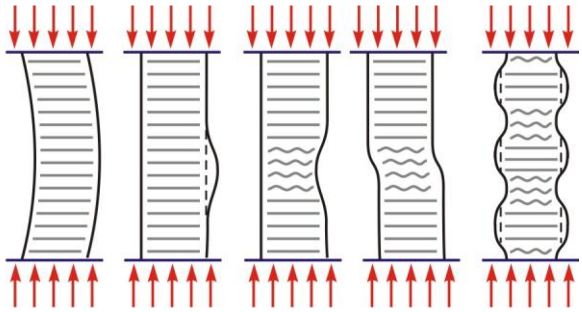
The notation $[0^o/90^o]_{2S}$ means that the laminate is assembled with two layers oriented at 0^o and 90^o.



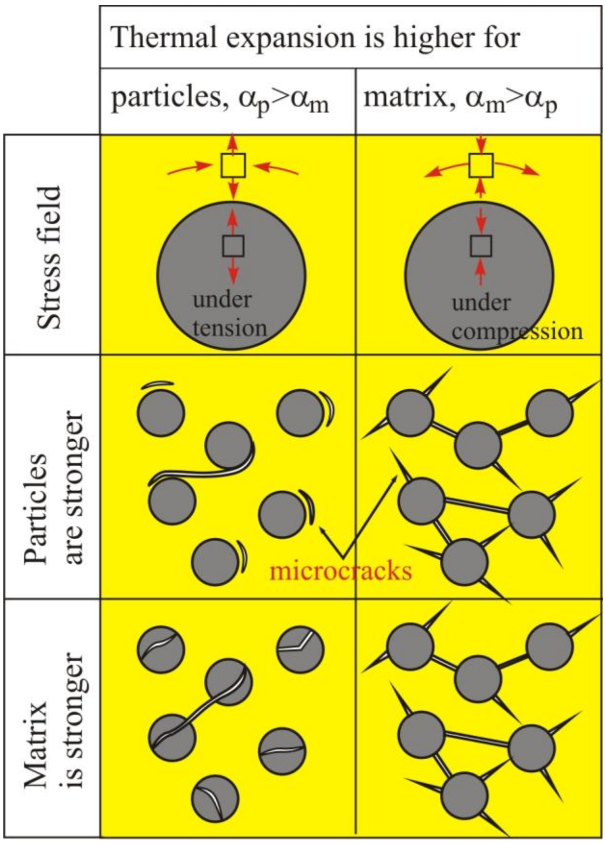
Tensile and shear stresses cause different failure scenarios for composite structures.



A honeycomb composite structure has high flexural strength. The mechanisms of stability loss under compression depends on many factors, such as adhesive quality, size of honeycomb, fiber filament, and other factors.

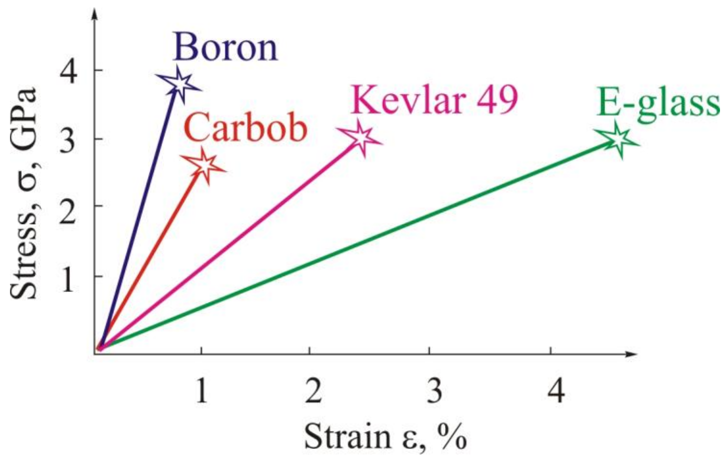


There is residual technological microcracking in composites reinforced by particles. If thermal expansion is high for particles, then the particles are under compression after cooling. Weak particles contain internal microcracks. If the matrix or bond border is weaker than particles, then there are tangential microcracks in the matrix and at the border.

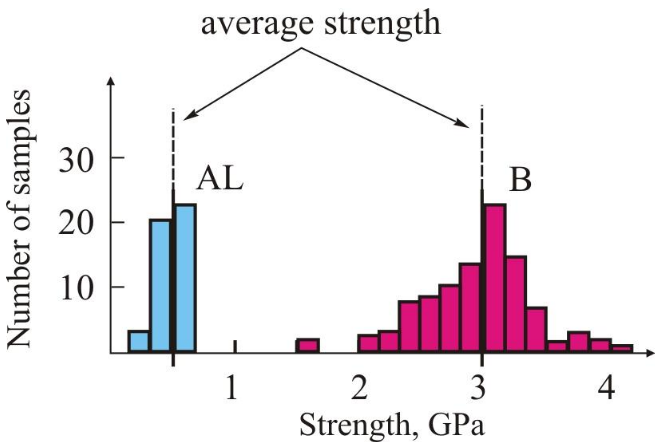


9.2 FIBERS

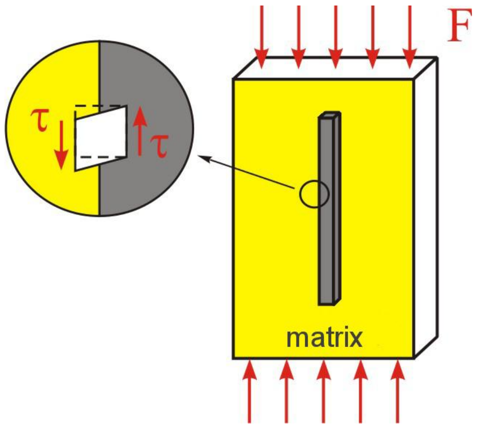
Fibers demonstrate unique mechanical properties: modulus of elasticity and strength. The critical force for a fiber is equal to the production of critical stress (strength) by the fiber area. Knotted aramid fiber maintains up to 50% of its original strength. Other fibrous materials are more brittle. There is small effect of temperature and deformation rate on the strength of brittle fibers, such as boron or SiC.



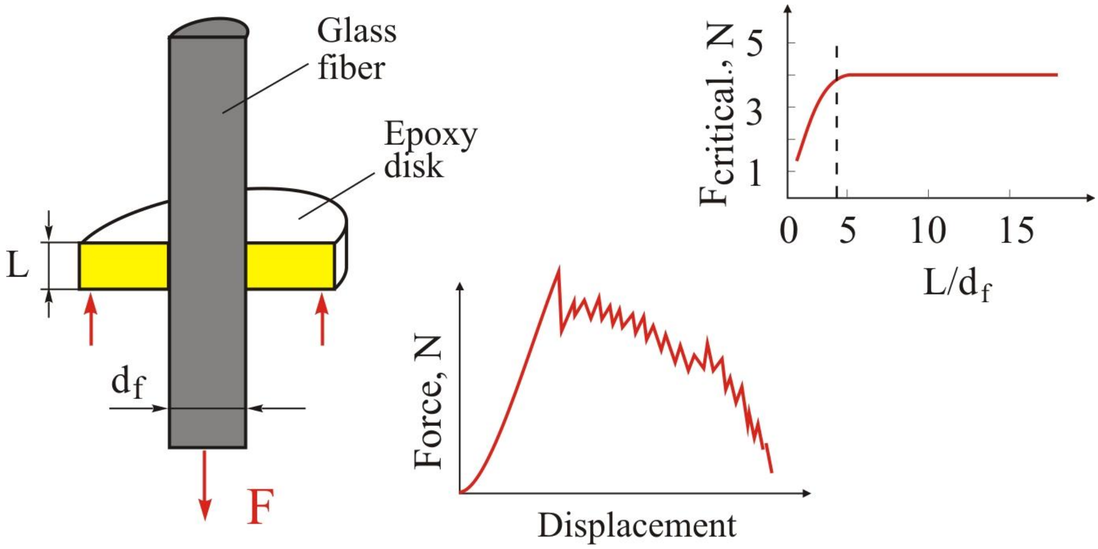
Fibers differ from other structural materials due to a larger scatter in experimental data.



Shear stress causes fracture of the fiber-matrix bond. Usually, fibers are round. Larger bond surfaces between matrix and fiber correspond to higher crack resistance.

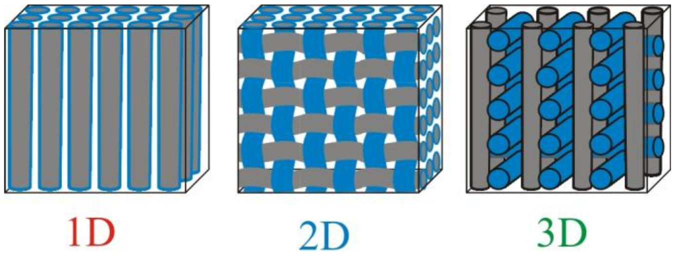


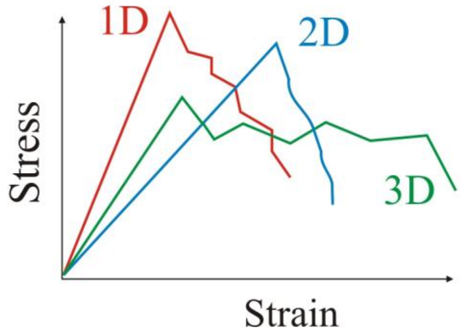
The effect of friction between matrix and fiber after bond fracture is reflected in a ”force-displacement” diagram. Critical forces depend on bond length for small L only.



9.3 RIGIDITY

The modulus of elasticity (Young's modulus) is a measure of rigidity. Modulus of elasticity has units of stress - [GPa] or [MPa].

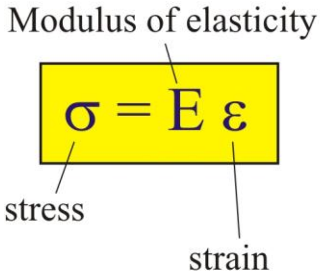


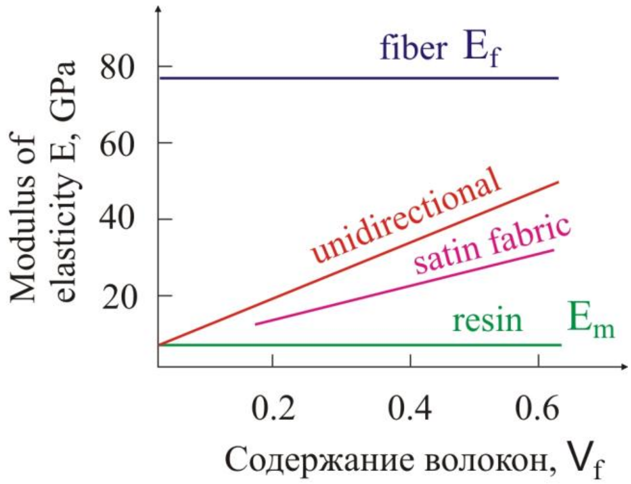


The modulus of elasticity of a composite material depends on the component's parameters, fiber content, and structure of the composite.

Boron, aramid, and carbon fibers are more rigid than aluminum or epoxy matrix:

$$\mathbf{E_f >> E_m}$$



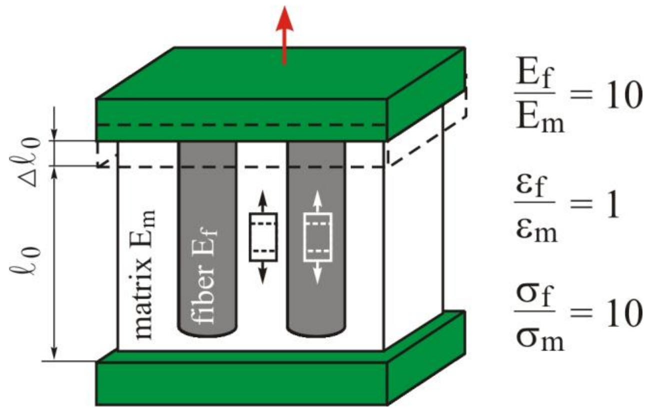


$$E=(E_f-E_m)V_f+E_m$$

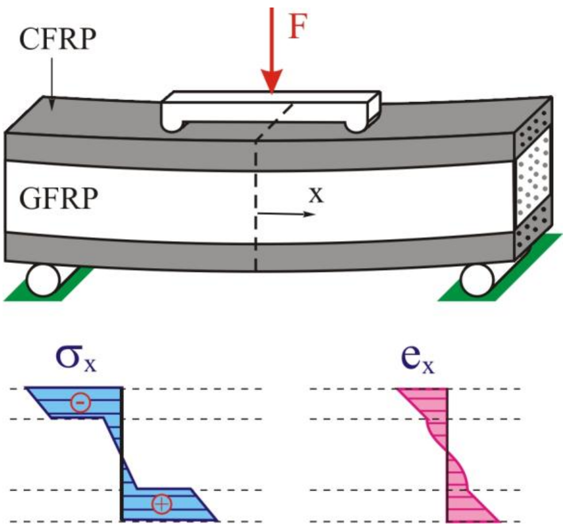
$$E=(\alpha E_f-E_m)V_f+E_m$$

$$\alpha=0{,}5$$

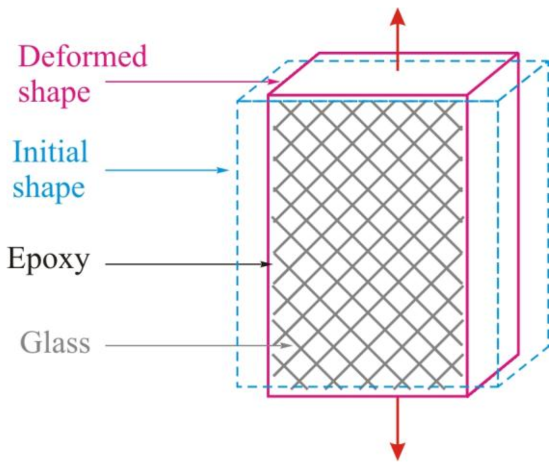
Both the matrix and fibers have the same strain under tension.
Stress is higher in the more rigid component.



The stress pattern in a composite beam demonstrates higher stress in rigid components and in external layers. Local delamination and voids have a small effect on the flexural stiffness of the composite beam.

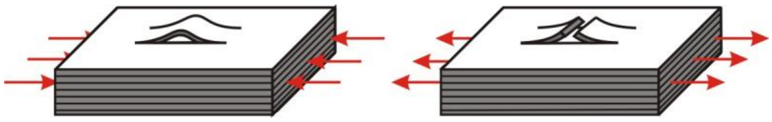


Poisson's ratio is a measure of transverse deformation under tension (compression). An ordinary value of Poisson's ratio is 0.3 for steels. Below is a lay-up scheme for which transverse deformation in a composite is higher in the longitudinal direction. Here, Poisson's ratio is higher than 1.

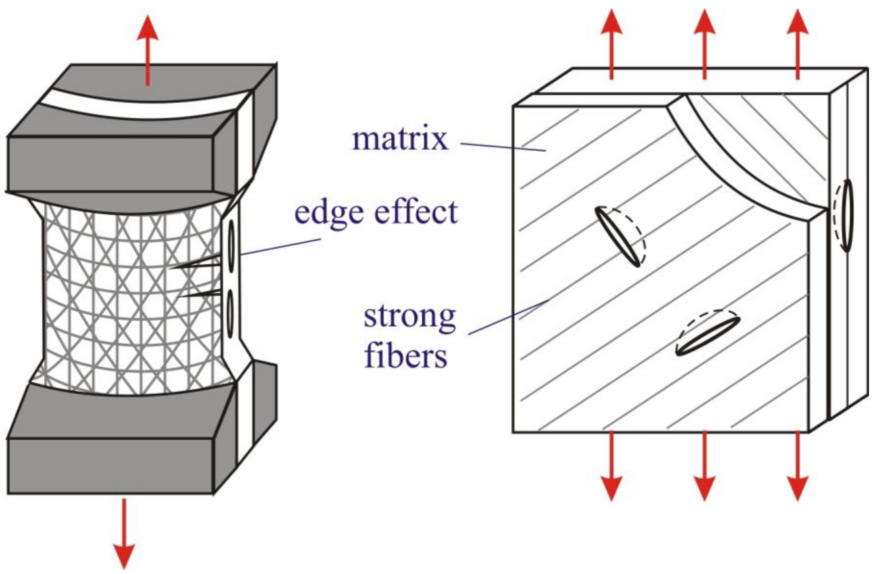


9.4 STRENGTH

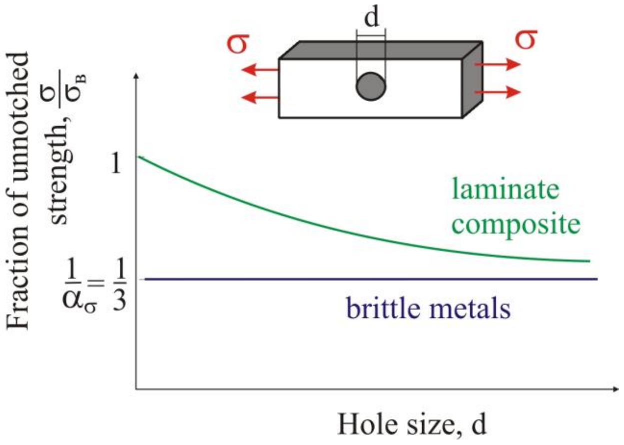
The mechanisms of fracture of a laminate are different under tension and compression. Surface layers can lose stability under compression.



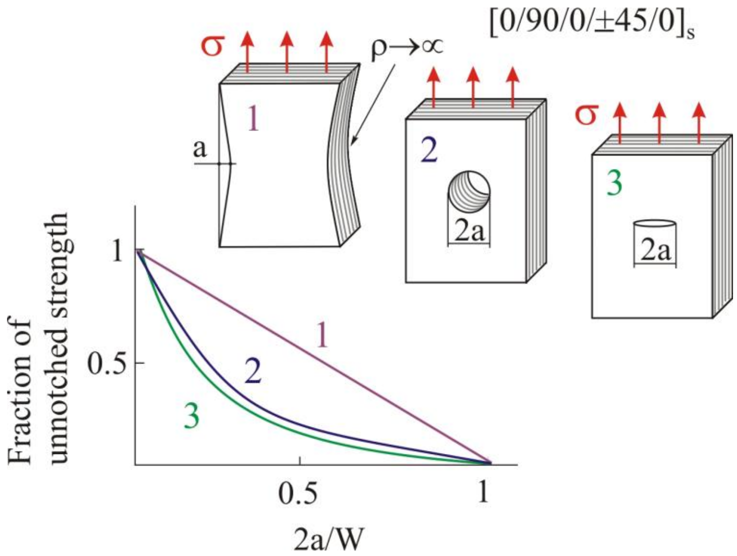
Inner defects and edges are sources of fracture initiation. Transfibrous defects are the most dangerous. Delamination has no great effect on strength of the composite system.



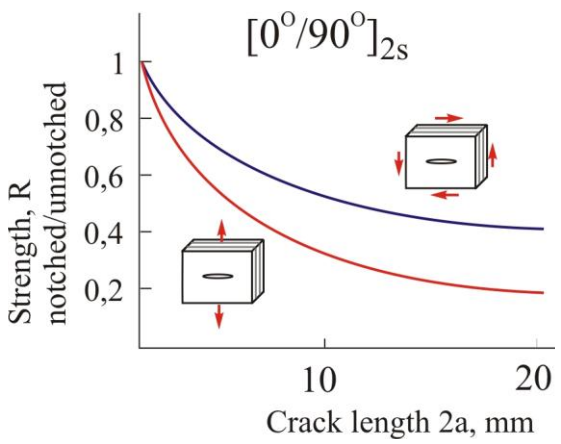
Holes and cracks decrease the tensile strength of composites. Composite materials are less ”sensitive” to small defects.



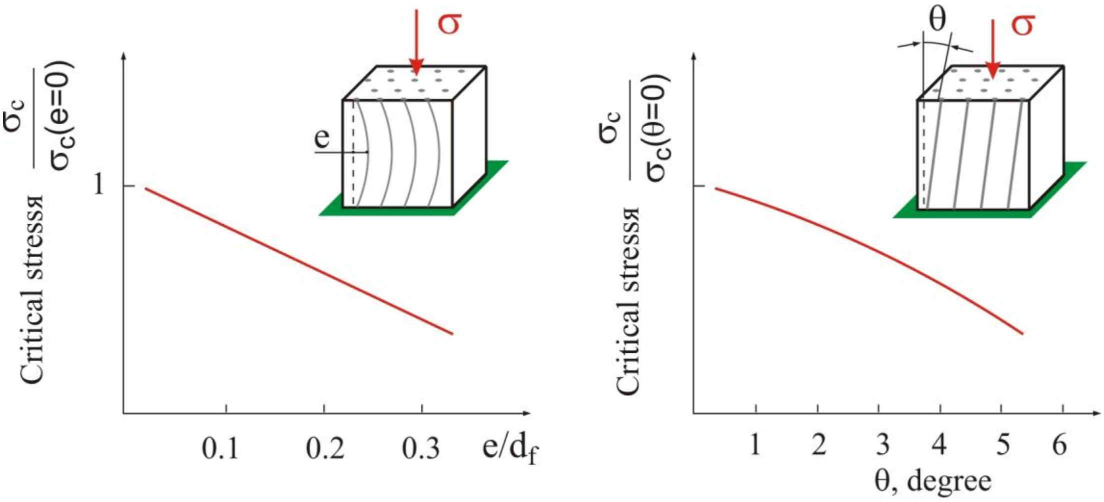
Cracks perpendicular to the applied load are more dangerous than a hole with the same maximum size.



Tensile strength decreases ”faster‟ than shear strength in the presence of voids and cracks in multilayer composites.

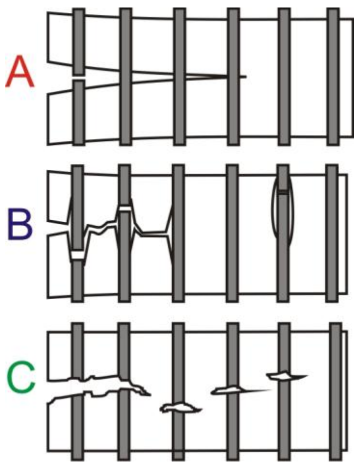


Curved and inclined fibers decrease the compression strength of the composite. The first factor is more critical in reducing the strength.

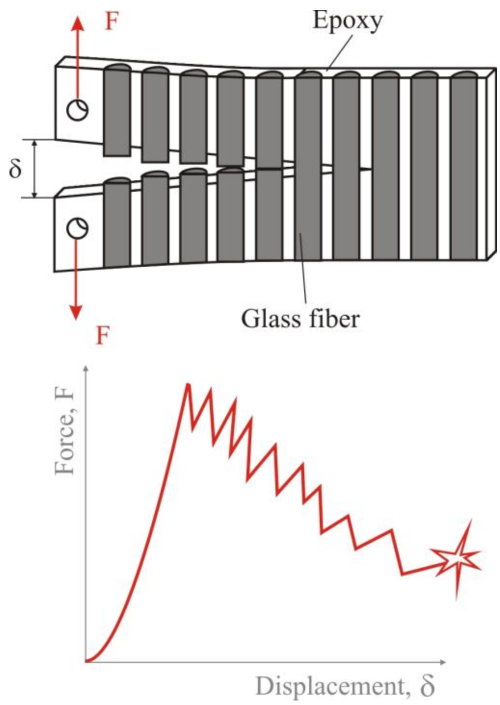


9.5 CRACK RESISTANCE

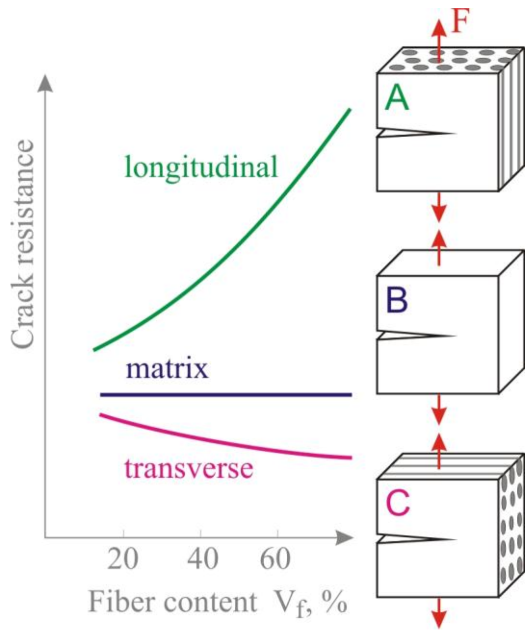
Multi-component materials demonstrate high crack resistance. Mechanical properties of the components and their bonds define the crack resistance of the composite, such as tensile strength of matrix (A - the property is low), bond strength (B), and tensile strength of fibers (C). A matrix with higher ductility and high-strength fibers have the higher crack resistance.



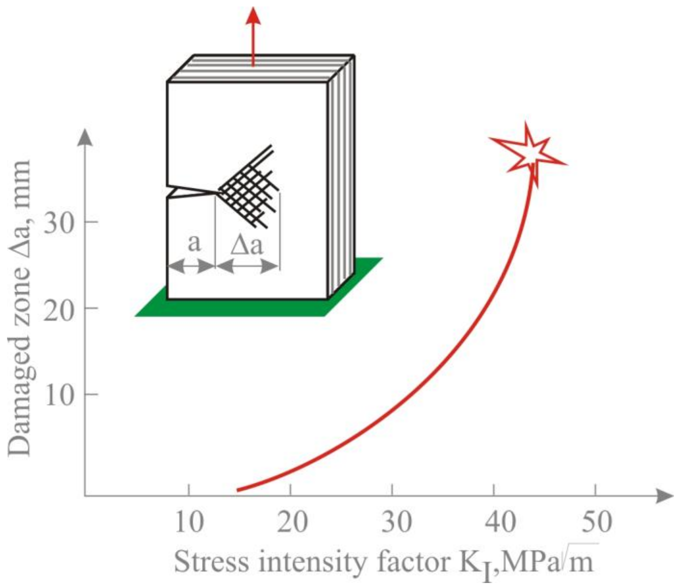
Each fiber breakage is reflected in a peak in the “force-displacement” diagram. The critical force for the first fiber is larger than for the others.



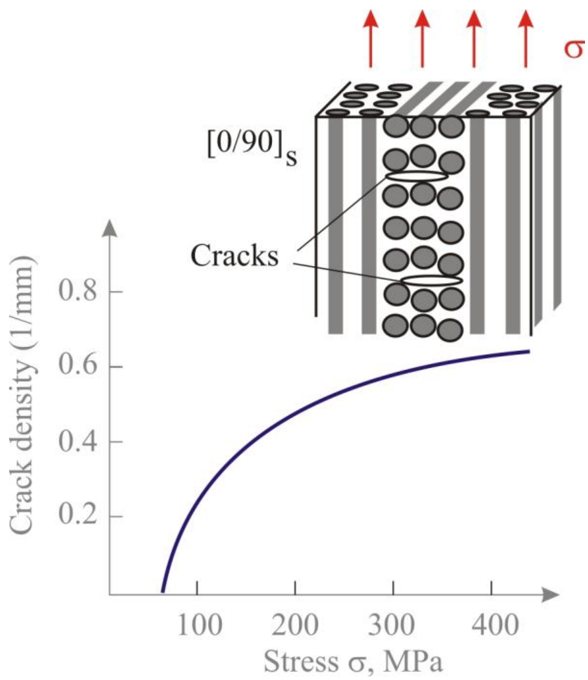
Unidirectional composites have a high crack resistance if the maximum tensile stress acts along the fibers. Tension in the transverse direction demonstrates a crack resistance that is lower than the same parameter for a ductile matrix.



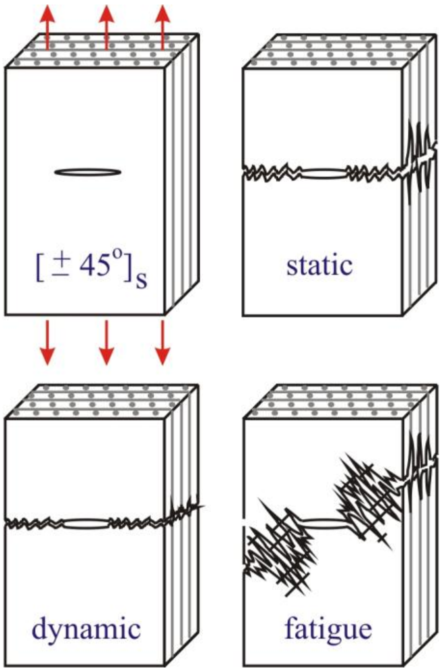
The damaged zone in the crack tip in a multi-directional laminate depends on the stress intensity factor (SIF). The SIF is the driving force in fatigue crack growth equations.



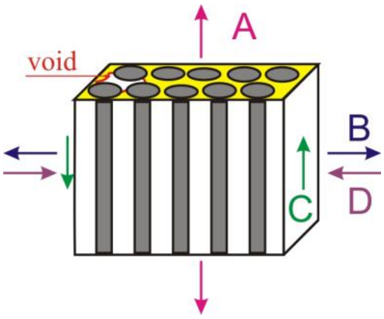
For $[0^o/90^o]_s$ lay-up, the transverse layer is the weakest. It starts to fracture through small microcracks, and the final failure occurs when the microcracks penetrate the longitudinal layer.



A specimen fractured in a fatigue test has a great deal of debonding and extracted fibers. Microdamage is less if the deformation rate is high.

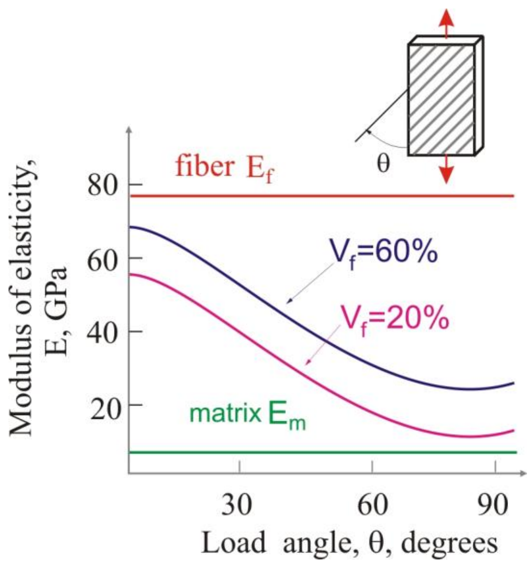


Voids in the matrix decrease the strength of unidirectional composites. The effect of strength decrease is highest for transverse tension and shear, and lower for tension along the fibers.

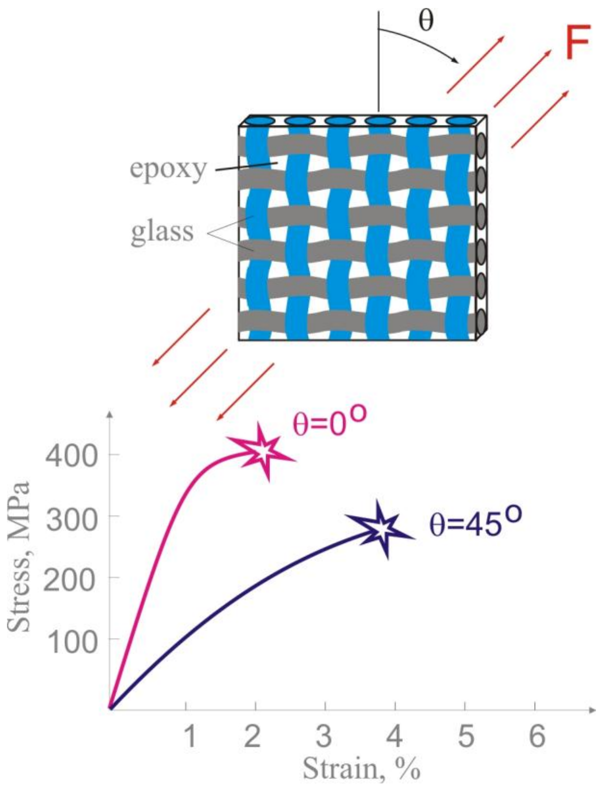


9.6 OPTIMIZATION

The angle between fiber direction and the tensile load will affect the stiffness of the composite layer. The stiffness and strength are higher if the maximum tensile load acts along the fibers.



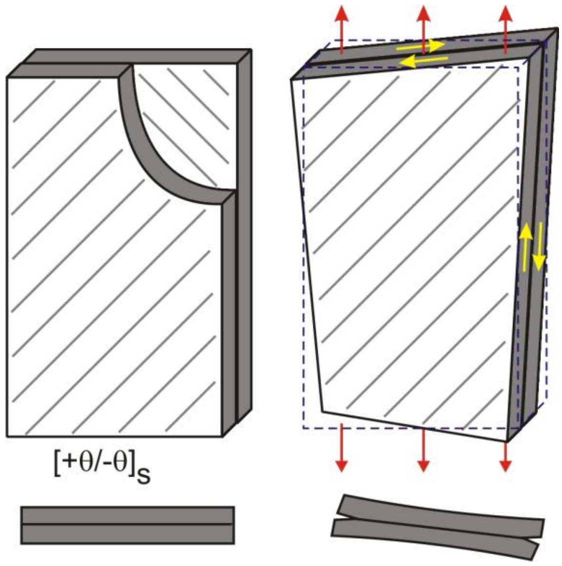
Stiffness of a fabric depends upon the load angle. An angle of 45^o corresponds to minimum rigidity. Stiffness of straight fibers is higher than that for curved fibers.



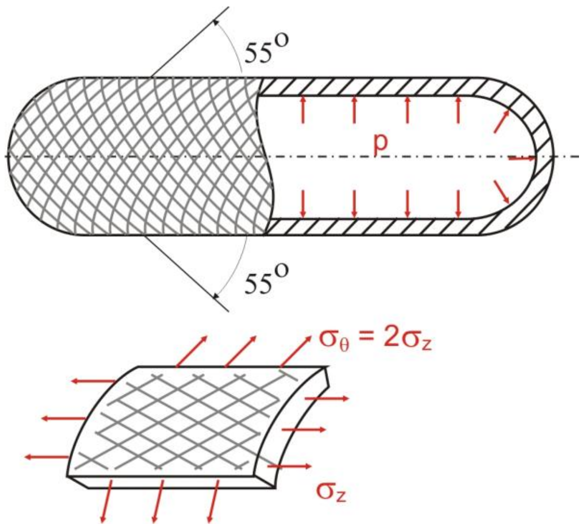
Fracture of a multi-directional laminate is a multi-stage process. First, the microstructural interlayer damage will take place at the edge of the plate.

Interlayer shear stress causes a coupling effect. The figure shows the cross-sectional areas of original and deformed plates.

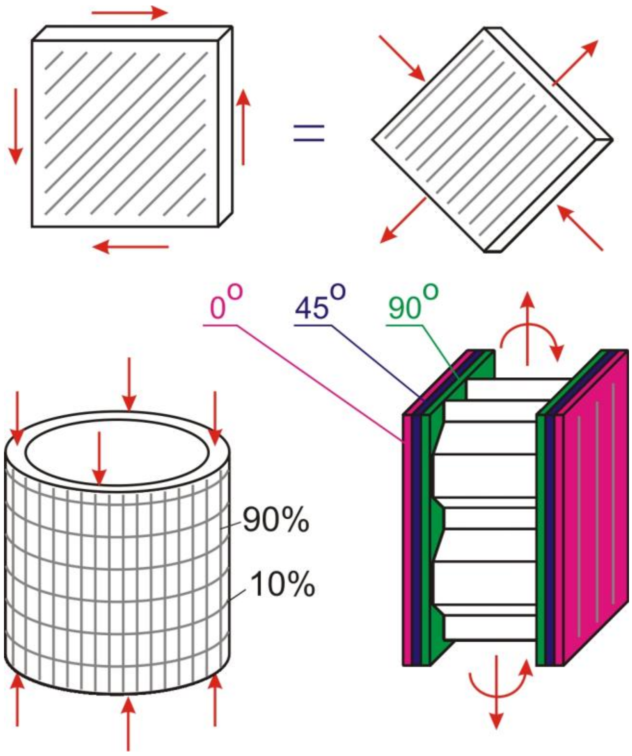
Multi-oriented laminate [0°/45°/90°/135°/...] has better notch resistance than a laminate with fewer fiber orientations [0°/90°].



Tangential stress in the pressure vessel is twice as large as radial stress. The stress ratio defines the optimal angle of two-directional lay-up: 55°.

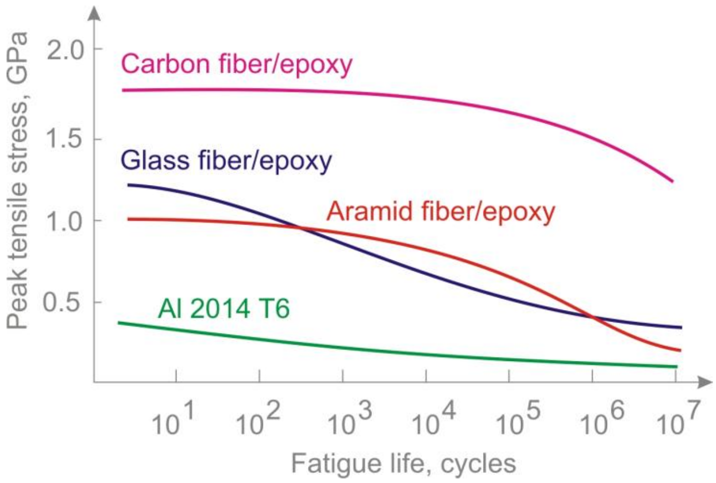


The optimal lay-up direction is coincident with the direction of the maximum inner force. An optimum honeycomb composite skin structure has symmetrical stacking, and its θ-oriented laminae are placed along the direction of the maximum tensile stress at external surfaces.

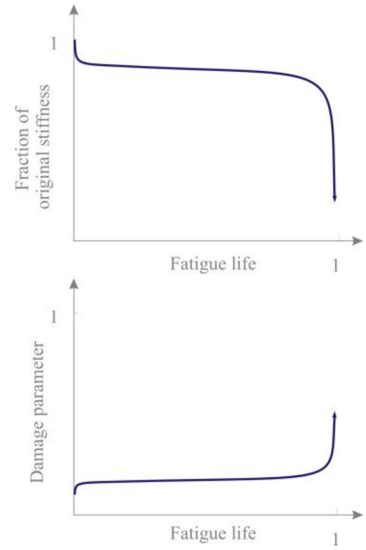


9.7 FATIGUE AND TEMPERATURE EFFECT

Composites demonstrate a high resistance to fatigue crack growth. The fatigue strength of many composite materials is higher than for aluminum alloys.

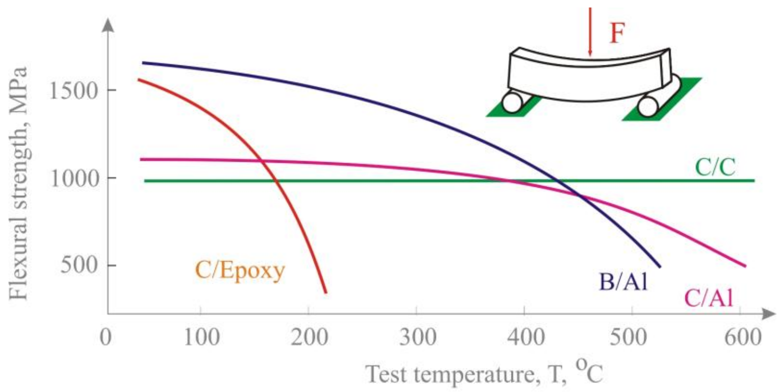


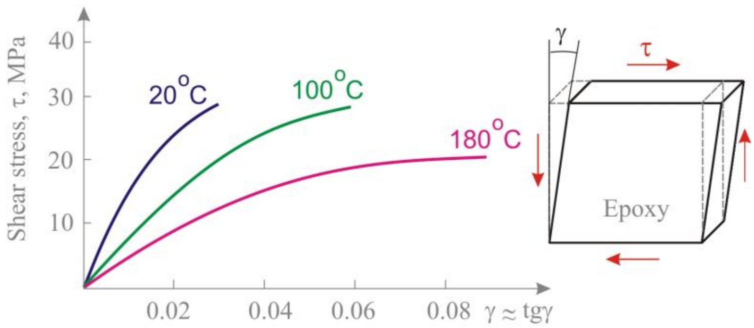
At the first stage of cycling, the "weak" fibers are broken. The composite does not fail at this stage due to redundancy of strength. Delamination and microstructural bond damage occurs over a long period of time. At the final stage, the number of broken fibers increases catastrophically.

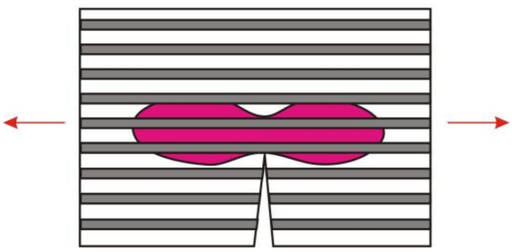


Industrial fibers are less sensitive to high temperature than epoxy or plastics. Carbon fibers demonstrate unique properties.

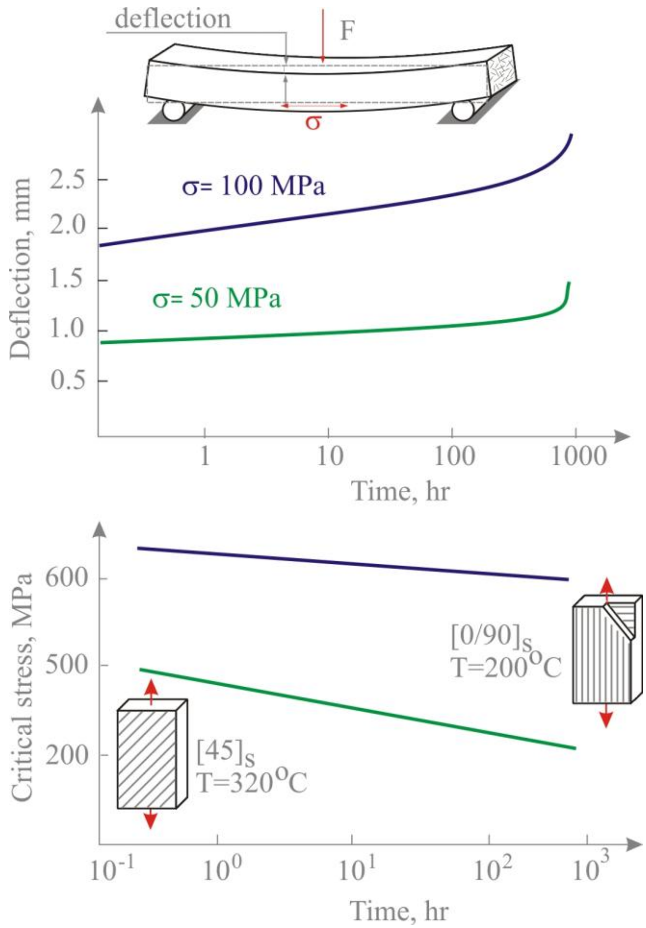
The zone of nonlinear deformation in the crack tip - zone of plasticity occurs in the matrix only.



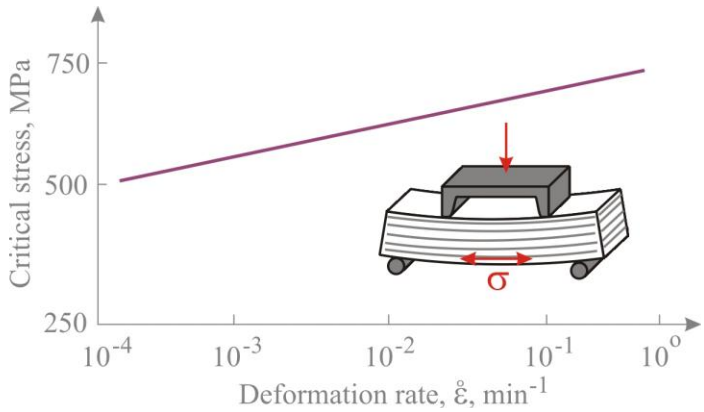




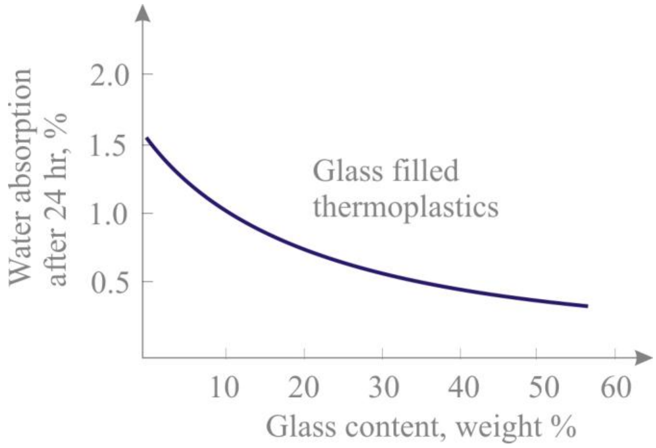
The creep rate increases as nominal stress increases. The ductility of the matrix contributes significantly to the creep effect. Reinforcement by strong and rigid fibers along the direction of the force leads to higher creep strength.



Glass fiber becomes more brittle and weaker at the “explosive" deformation rate - small values of the parameter.

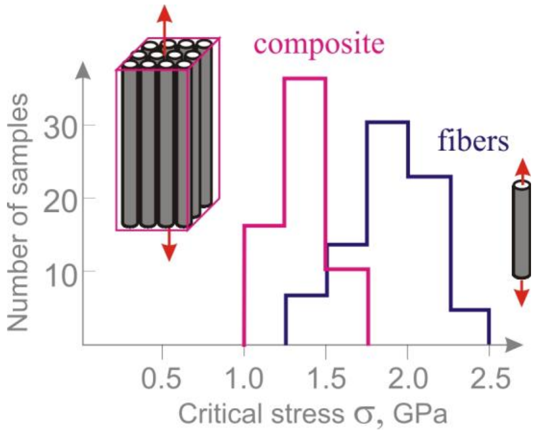


Water absorption of glass-filled thermoplastics decreases as glass content increases. Water absorption decreases the strength of the composite.

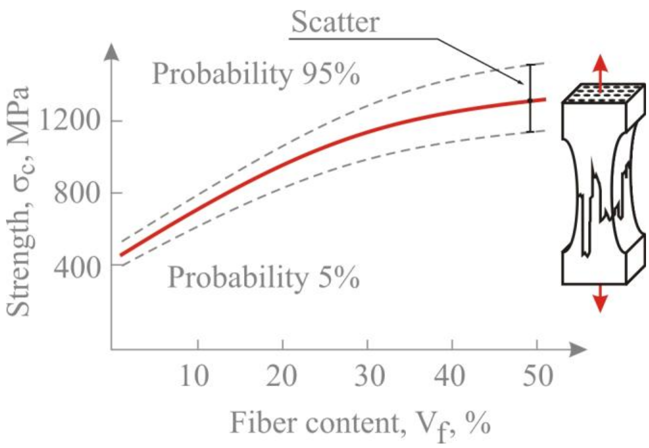


9.8 RELIABILITY

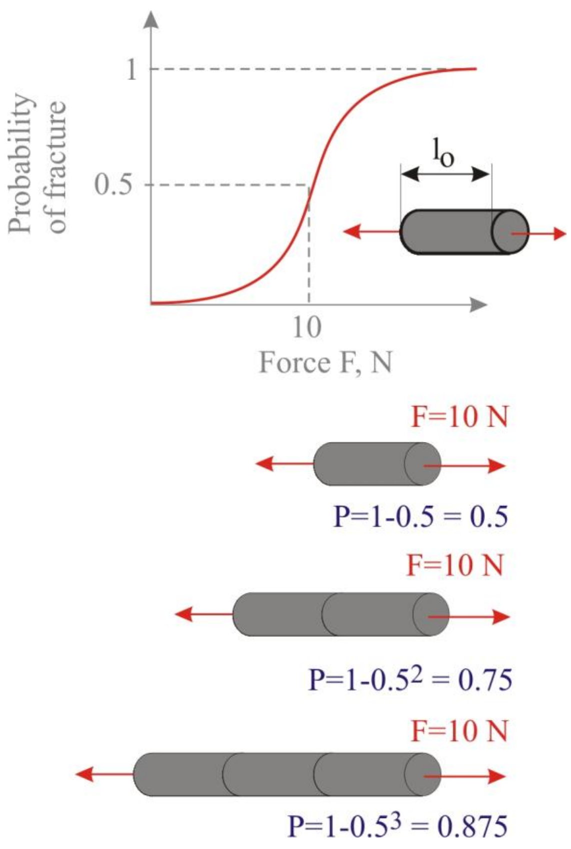
A specific feature of composites is high scatter in strength of strong fibers. Composites usually have lower average strength and scatter compared to fibers.



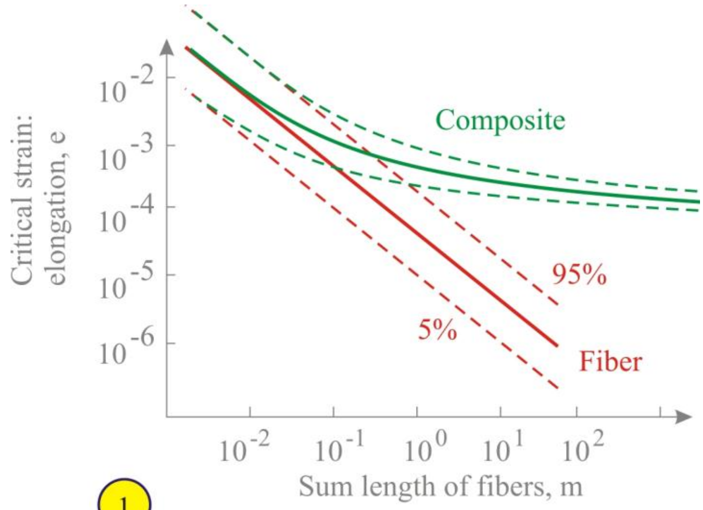
For constant average strength and higher scatter, there is a higher probability that microcracks in the weakest fibers are surrounded by strong fibers. The ultimate strength of such composites is usually high.

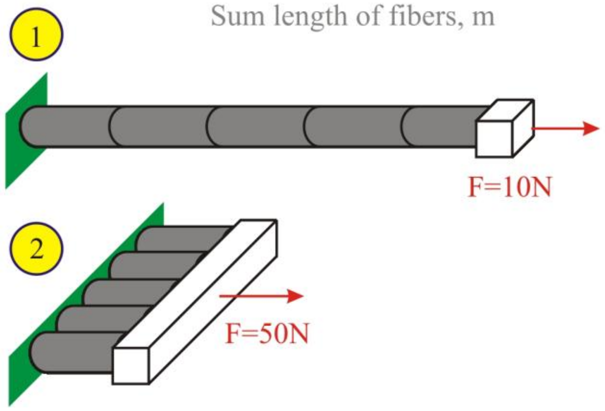


Higher average strengths correspond to higher scatter in experimental data. This rule is valid for fibers and composite materials.



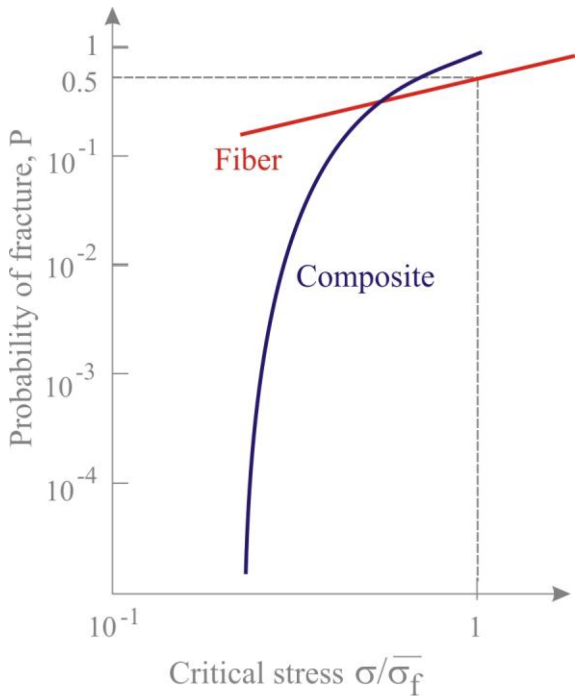
If the probability of fracture of a fiber with length l_o is 0.5, then the probability of failure of a longer fiber is higher. Fibers with longer length have lower strength. Composite series-parallel structures do not decrease the strength to zero due to strength redundancy of parallel elements.



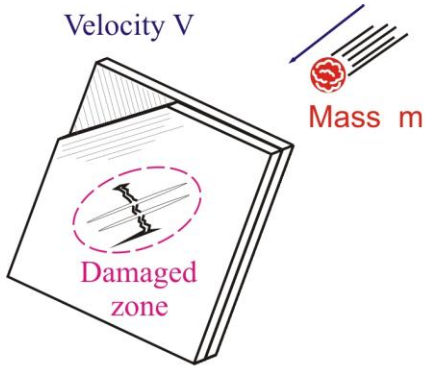


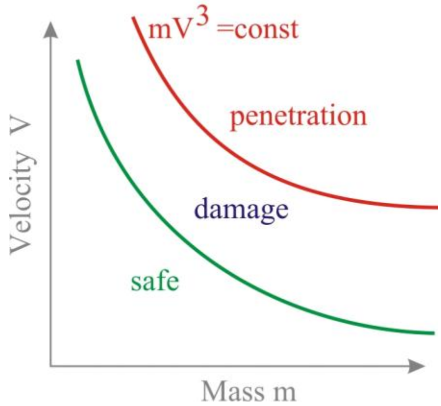
The probability of failure of a series structure composed of similar elements (fibers) is higher than that for a parallel structure.

The average strength of a composite is less than the average strength of its fiber. At low stress, the probability of fracture of a composite (series-parallel system) is lower than for fibers.

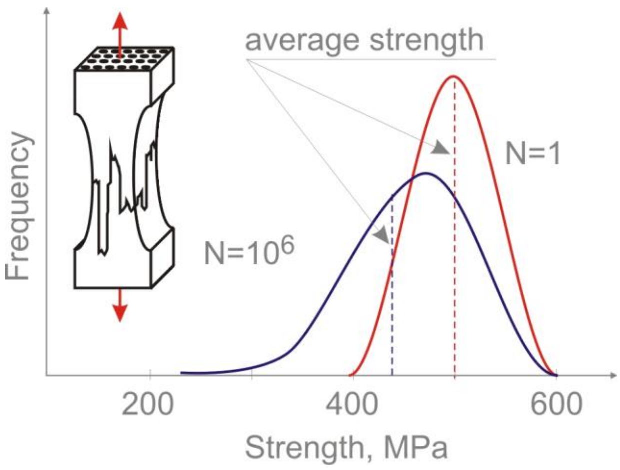


Experimental data show that the condition of penetration of a flying body depends on its mass and velocity. The damage decreases fatigue strength of the laminate.



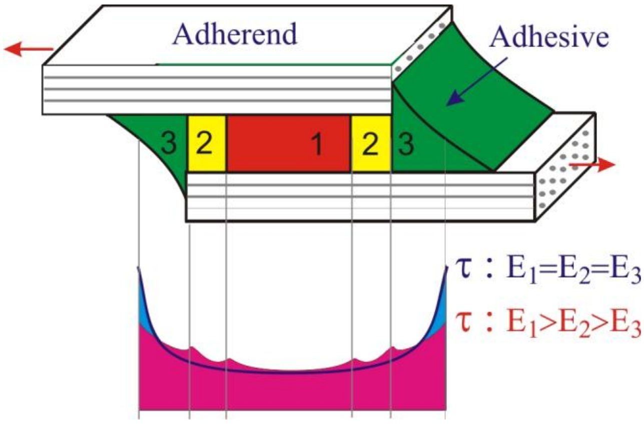


Cyclic loading (fatigue microdamage) decreases the remaining static strength of a composite structure.

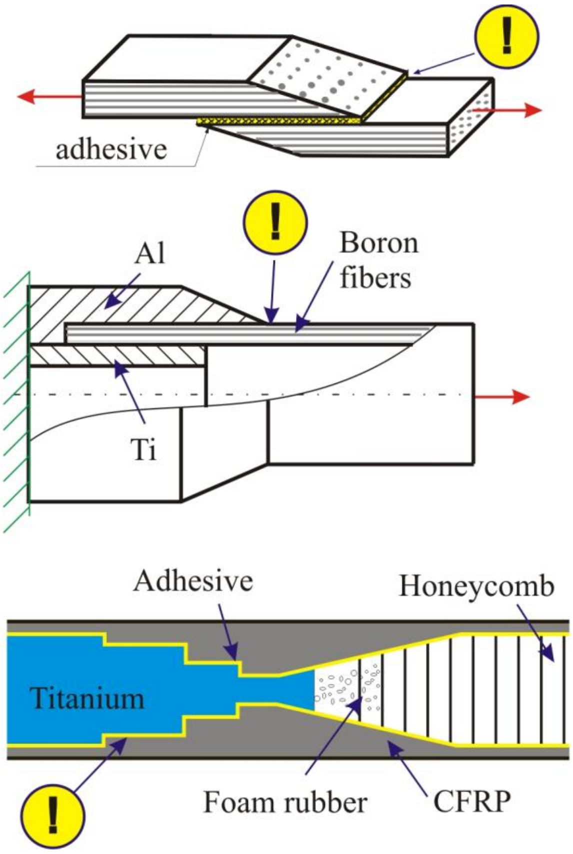


9.9 JOINTS

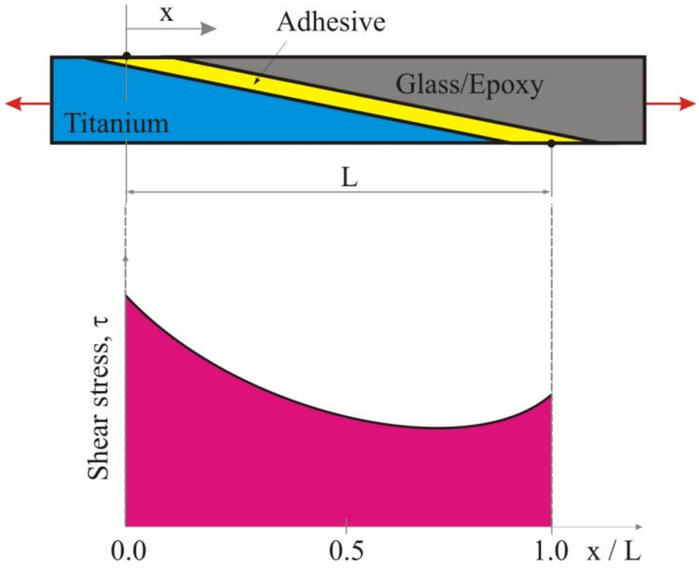
There is high stress concentration in the lap joint. It can be decreased if the Young's modulus of the adhesive decreases at the edges.



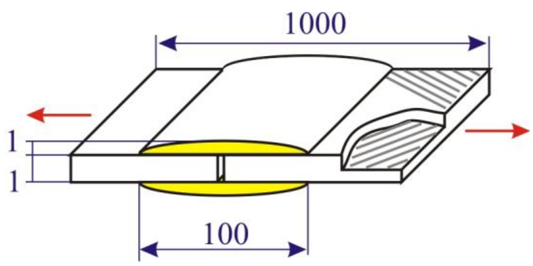
Stress concentration is smaller for a "smooth" transition from one structural element (adherent) to another.



Stress concentration is higher in a more rigid material. Proper laminar orientation can decrease the stress concentration.

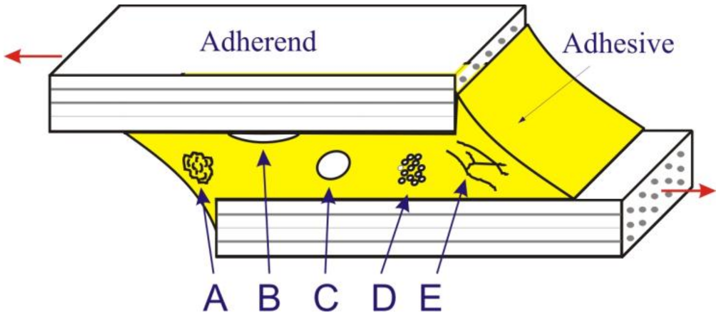


The joint's bond surface must be sufficiently larger than its cross-sectional area. The joint can be reinforced by fabric fibers.



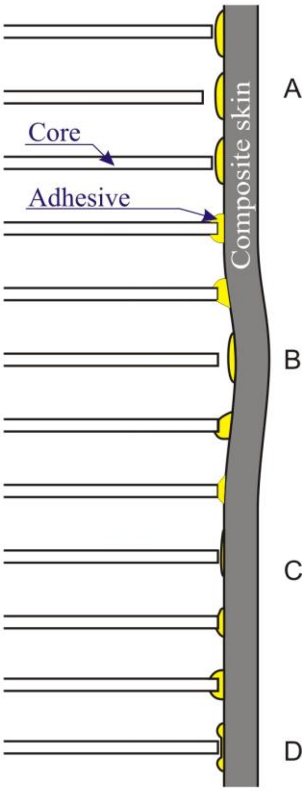
Manufacturing defects in the adhesive can decrease strength of joints and can be detected by nondestructive testing. The following are examples of some defects:

A. Matrix cure is caused by incorrect mixing or thermal exposure.
B. Disbond or zero-volume unbond is caused by incorrect surface preparation.
C. Voids can be caused by air entrapment.
D. Porosity is associated with volatiles and entrained gases.
E. Adhesive cracks can be caused by thermal shrinkage during manufacturing.

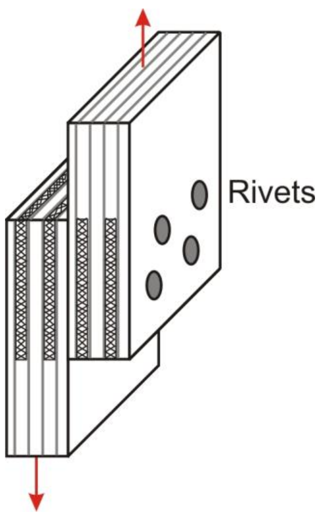


Composite honeycomb structures have high flexural stiffness and strength. Defects decrease flexural and compressive strength of honeycomb structures:

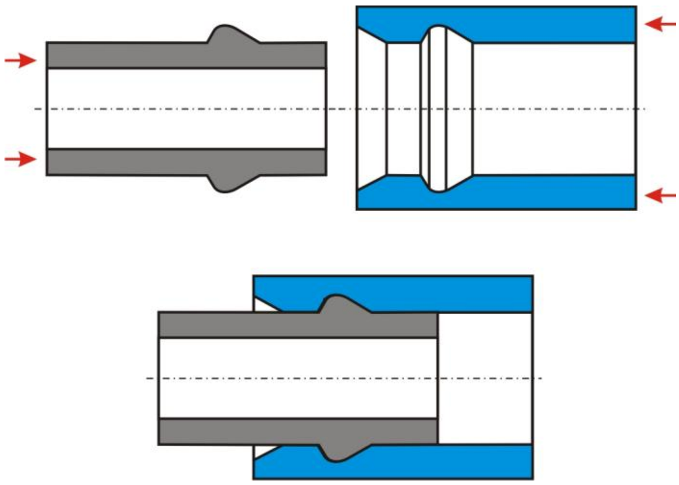
A. Core damage.
B. Skin imperfection.
C. Lack of adhesive.
D. Improperly formed adhesive fillet.



Rivets are widely used in a composite skin connection. Strength of rivet joints can be increased by increasing the number of smaller rivets and/or by metal foil reinforcement.

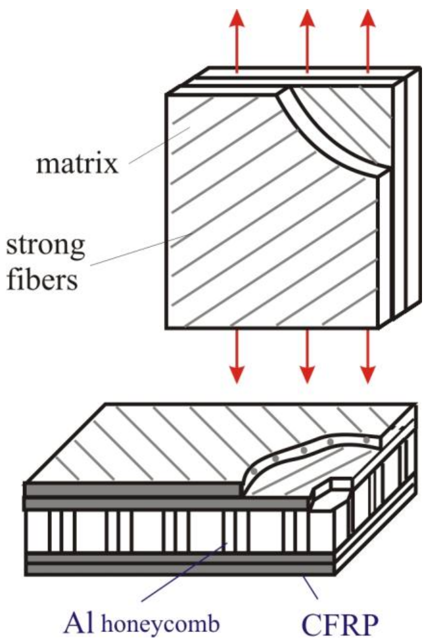


Connection of the composite tubes can be made by elastic deformation in the composites. Filament winding increases the carrying ability of the joint.

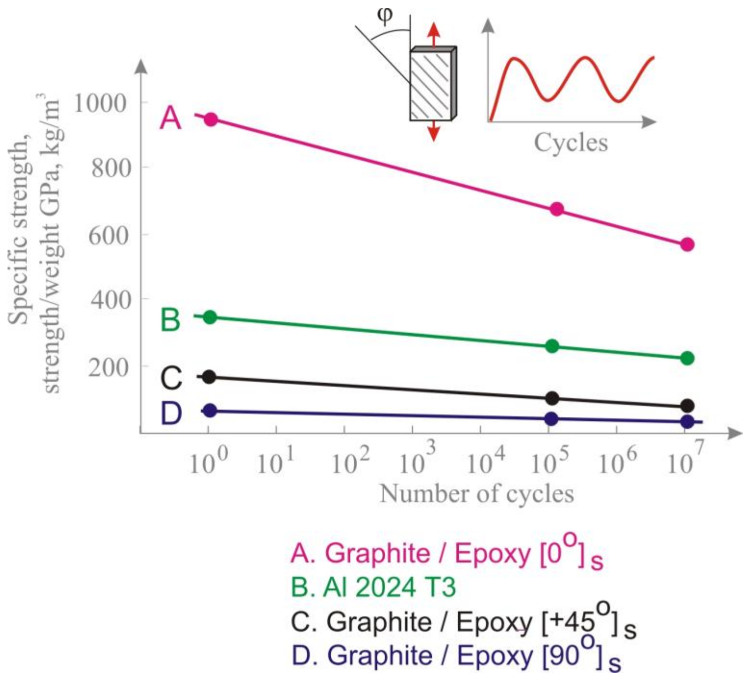


9.10 MATERIAL SELECTION

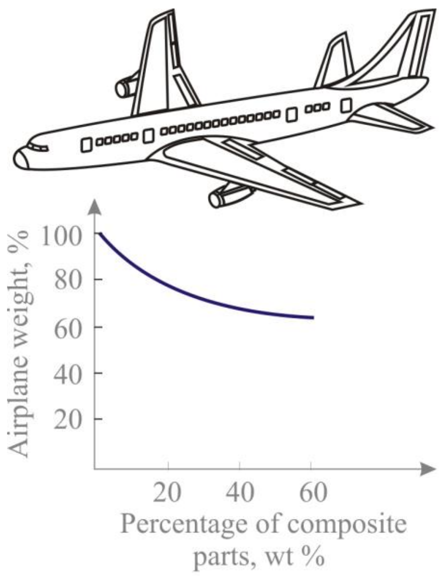
Advanced composite materials have unique mechanical properties compared to steel or aluminum alloys, including fatigue strength, specific strength (ratio of strength to weight), specific rigidity (ratio of modulus of elasticity to weight), strength redundancy, and high resistance of damaged structures to external loads. In contrast to metals, the crack resistance of modern composite materials increases as strength increases. The crack resistance of composite materials depends on fiber tensile strength, its scatter, matrix tensile strength, and bond shear strength. Splitting the bond between the matrix and fiber helps stop macrocracks in materials.

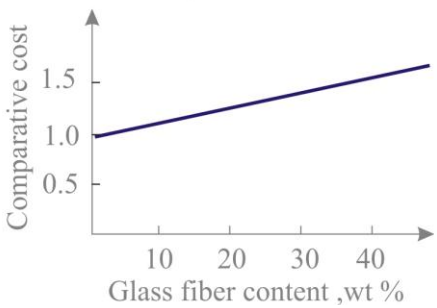


Unique properties of a composite can be obtained by proper choice of filament, fiber content, layer orientation, and other parameters.



The use of composite materials decreases the weight of a passenger airplane by 20 - 40%. Use of composite materials decreases the cost of many engineering structures. An increase in fiber content does not excessively raise the cost of the composite.



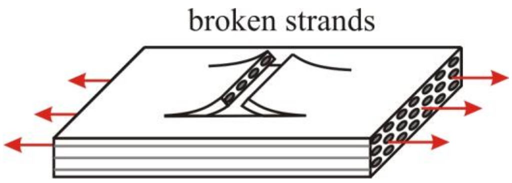


One of the most important stages of composite structure manufacturing is nondestructive testing:

A. Ultrasonic testing can reveal porosity, voids, incorrect volume fraction, foreign inclusions, translaminar cracks, delaminations, disbonds in adhesive, and poor fillet in honeycomb construction.
B. An eddy currents technique is limited to materials with a conducting phase.
C. Thermography can be used as a rapid technique for inspecting large-scale composite structures.
D. Holography is a very expensive technique with a restricted list of discovered defects, such as disbonding and delamination.
E. Radiography is used in testing of boron or glass reinforced composites, but not carbon fiber reinforced composites.

Ultrasonic testing is the most widely used technique for many composite materials.

Group fiber breakage is the most dangerous defect in a composite. It can be revealed by one of the nondestructive methods from the above list.



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