TESTING OF COMPOSITES - II

STATIC MECHANICAL PROPERTIES

Static mechanical properties, such as tensile, compressive, flexural, and shear properties, of a material are the basic design data in many, if not most, applications.

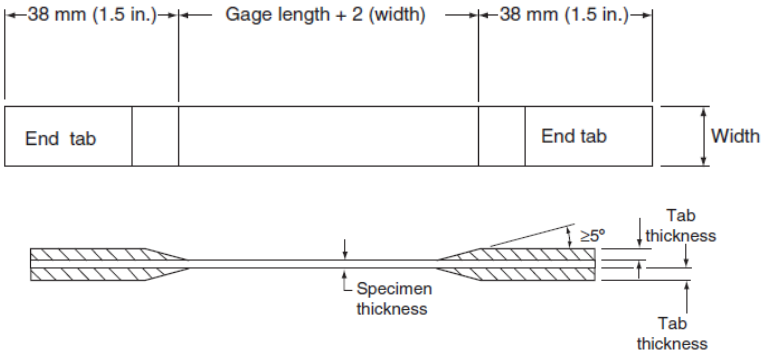
Mechanical properties of a composite

1. Tensile properties
2. Compressive properties
3. Flexural properties
4. In-plane shear properties
5. Interlaminar shear strength
6. Impact properties

TENSILE PROPERTIES

Test Method and Analysis

Tensile properties, such as tensile strength, tensile modulus, and Poisson's ratio of flat composite laminates, are determined by static tension tests in accordance with ASTM D3039. The tensile specimen is straight-sided and has a constant cross section with beveled tabs adhesively bonded at its ends (Figure 4.1).

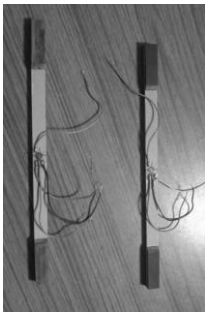


Tensile test specimen configuration

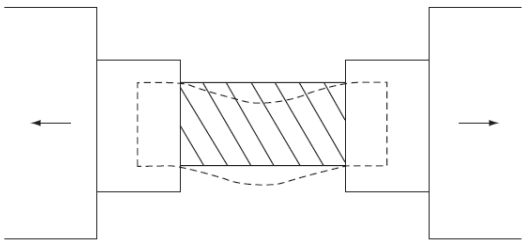
A compliant and strain-compatible material is used for the end tabs to reduce stress concentrations in the gripped area and thereby promote tensile failure in the gage section. Any high-elongation (tough) adhesive system can be used for mounting the end tabs to the test specimen.

Specimens with the dimension of 250 mm X 12.50 mm X 2.4 mm with end tabs (45 mm X 12.50 mm X 3 mm) were used for testing. The tensile specimen is held in a testing machine by wedge action grips and pulled at a recommended cross-head speed of 2 mm/min. Longitudinal and transverse strains are measured employing

electrical resistance strain gages that are bonded in the gage section of the specimen. Longitudinal tensile modulus E_{11} and the major Poisson's ratio v_{12} are determined from the tension test data of 0° unidirectional laminates. The transverse modulus E_{22} and the minor Poisson's ratio v_{21} are determined from the tension test data of 90° unidirectional laminates.



For an off-axis unidirectional specimen ($0° < \theta < 90°$), a tensile load creates both extension and shear deformations. Since the specimen ends are constrained by the grips, shear forces and bending couples are induced that create a nonuniform S-shaped deformation in the specimen.



Nonuniform deformation in a gripped off-axis tension specimen.

For this reason, the experimentally determined modulus of an offaxis specimen is corrected to obtain its true modulus.

$$E_{\text{true}} = (1 - \eta)\, E_{\text{experimental}},$$

where

$$\eta = \frac{3\bar{S}_{16}^2}{\bar{S}_{11}^2[3(\bar{S}_{66}/\bar{S}_{11}) + 2(L/w)^2]},$$

where

L is the specimen length between grips

w is the specimen width

$\bar{S}_{11}, \bar{S}_{16}$, and $\bar{S}_{66}$ are elements in the compliance matrix

The value of η approaches zero for large values of L/w. Based on the investigation, L/w ratios >10 are recommended for the tensile testing of off-axis specimens. The

inhomogeneity of a composite laminate and the statistical nature of its constituent properties often lead to large variation in its tensile strength. Assuming a normal distribution, the average strength, standard deviation, and coefficient of variation are usually reported as

$$\text{Average strength} = \sigma_{\text{ave}} = \sum \frac{\sigma_i}{n},$$

$$\text{Standard deviation} = d = \sqrt{\frac{\sum (\sigma_i - \sigma_{\text{ave}})^2}{(n-1)}},$$

$$\text{Coefficient of variation} = \frac{100d}{\sigma_{\text{ave}}},$$

where

n is the number of specimens tested

s_i is the tensile strength of the i^{th} specimen

Example: Failure modes in Unidirectional Laminates

For unidirectional polymer matrix laminates containing fibers parallel to the tensile loading direction (i.e. θ = 0°), the tensile stress–strain curve is linear up to the point of failure (Figure 4.4). These specimens fail by tensile rupture of fibers, which is followed or accompanied by longitudinal splitting (debonding along the fiber–matrix interface) parallel to the fibers. This gives a typical broom-type appearance in the failed area of 0° specimens (Figure 4.5a). For off- axis specimen with 0°< θ < 90°, the tensile stress–s train curves may exhibit nonlinearity. For 90° specimens in which the fibers are 90° to the tensile loading direct ion, tensile rupture of the matrix or the fiber –matrix inter face causes the ultimate failure. For intermediate angles, failure may occur by a combination of fiber–matrix interfacial shear failure, matrix shear failure, and matrix tensile rupture. For many of these off-axis specimens (including 90°), matrix craze marks parallel to the fiber direct ion may appear throughout the gage length at low loads. Representative failure profiles for these specimens are shown in Figure 4.5b and c. Both tensile strength and modulus for unidirectional specimens depend strongly on the fiber orientation angle θ (Figure 4.6). The maximum tensile strength and modulus are at θ = 0°. With increasing fiber orientation angle, both tensile strength and modulus are reduced. The maximum reduction is observed near θ = 0° orientations.

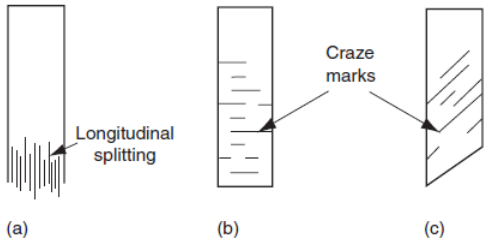


FIGURE 4.5 Schematic failure modes in unidirectional laminates: (a) $\theta = 0°$, (b) $\theta = 90°$, and (c) $0 < \theta < 90°$.

COMPRESSIVE PROPERTIES

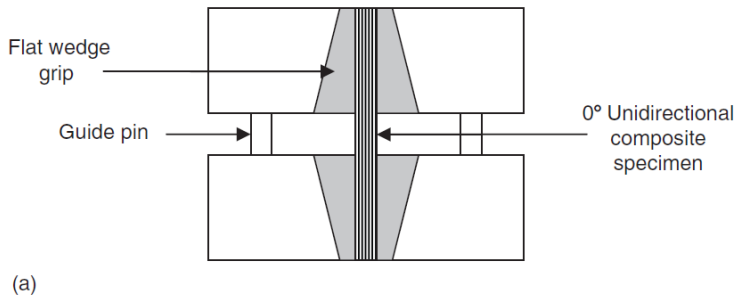
Compressive properties of thin composite laminates are difficult to measure owing to sidewise buckling of specimens. A number of test methods and specimen designs have been developed to overcome the buckling problem. Three of these test methods are described as follows.

1. Celanese test
2. IITRI test
3. Sandwich edgewise compression test

Celanese test: This was the first ASTM standard test developed for testing fiber-reinforced composites in compression; however, because of its several deficiencies, it is no longer a standard test.

IITRI test: The IITRI test was first developed at the Illinois Institute of Technology Research Institute and was later adopted as a standard compression test for fiber reinforced composites (ASTM D3410). It uses flat wedge grips to hold the specimen as shown in below figure. Flat wedge surfaces provide a better contact between the wedge and the collets and improve the axial alignment. Flat wedge grips can also accommodate variation in specimen thickness. The IITRI test fixture contains two parallel guide pins in its bottom half that slide into two roller bushings that are located in its top half. The guide pins help maintain good lateral alignment between the two halves during testing. The standard specimen length is 140 mm, out of which the middle 12.7 mm is unsupported and serves as the gage length. Either untabbed or tabbed specimens can be used; however, tabbing is preferred, since it prevents surface damage and end crushing of the specimen if the clamping force becomes too high.

Compression test specimens with the dimension of 114 mm X 12.5mm X 2.4 mm with end tabs (50 mm X 12.4 mm X 3 mm) can be used for testing.



(a)

Compressive test data on fiber-reinforced composites are limited. From the available data on 0° laminates, the following general observations can be made.

1. Unlike ductile metals, the compressive modulus of a 0° laminate is not equal to its tensile modulus.
2. Unlike tensile stress–strain curves, compressive stress–strain curves of 0° laminates may not be linear.
3. The longitudinal compressive strength of a 0° laminate depends on the fiber type, fiber volume fraction, matrix yield strength, fiber length–diameter ratio, fiber straightness; fiber alignment as well as fiber–matrix interfacial shears strength. The effects of some of these variables on the compressive properties of unidirectional fiber-reinforced polyester composites have been studied by Piggott and Harris and are described in Ref. [4].
4. Among the commercially used fibers, the compressive strength and modulus of Kevlar 49-reinforced composites are much lower than their tensile strength and modulus. Carbon and glass fiber-reinforced composites exhibit slightly lower compressive strength and modulus than their respective tensile values, and boron fiber-reinforced composites exhibit virtually no difference between the tensile and compressive properties.

FLEXURAL PROPERTIES

Flexural properties, such as flexural strength and modulus, are determined by ASTM test method D7264. In this test, a composite beam specimen of rectangular cross section is loaded in either a three-point bending mode (Figure 4.23a) or a four-point bending mode (Figure 4.23b). In either mode, a large span–thickness (L=h) ratio is recommended. Specimens with the dimension of 100 mm X 10 mm X 2.4 mm were used with a cross head speed of 1 mm/min. Fig 4.4 shows the schematic of flexural strength test. The maximum fiber stress at failure on the tension side of a flexural specimen is considered the flexural strength of the material. Thus, using a

homogeneous beam theory, the flexural strength in a three-point flexural test is given by

$$\sigma_{UF} = \frac{3P_{max}\,L}{2bh^2},$$

where

P_{max}= maximum load at failure

b = specimen width

h = specimen thickness

L = specimen length between the two support points

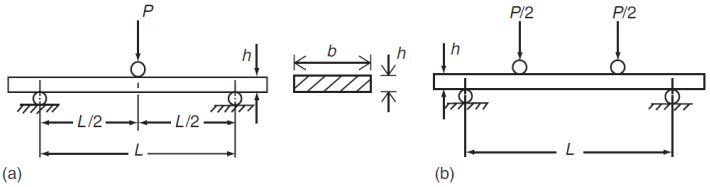


FIGURE 4.23 Flexural test arrangements in (a) three-point bending and (b) four-point bending modes.

Flexural modulus is calculated from the initial slope of the load–deflection curve:

$$E_F = \frac{mL^3}{4bh^3},$$

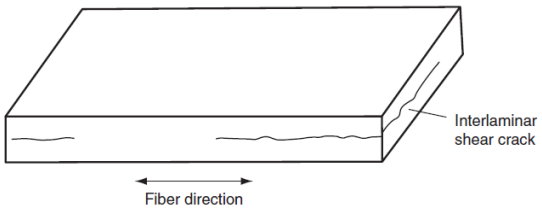
where m is the initial slope of the load–deflection curve. Three-point flexural tests have received wide acceptance in the composite material industry because the specimen preparation and fixtures are very simple.

INTERLAMINAR SHEAR STRENGTH

Interlaminar shear strength (ILSS) refers to the shear strength parallel to the plane of lamination. Short beam shear is used to determine interlaminar shear strength of a composite material test in accordance with ASTM D2344. The specimen is placed on a horizontal shear test fixture so that the fibers are perpendicular to the loading nose. The loading nose is then used to flex the specimen at a speed of 2 mm / minute until the breakage. The force is then recorded. Calculations are performed to determine shear strength. The specimen of size 20 mm X 10 mm X 2.4 mm were subjected to shear loading test fixture and measured the strength. A flexural specimen of small span–depth (L=h) ratio is tested in three-point bending to produce a horizontal shear failure between the laminas. To explain the short-beam shear test, let us consider the following homogeneous beam equations:

$$\text{Maximum normal stress } \sigma_{xx} = \frac{3PL}{2bh^2} = \frac{3P}{2bh}\left(\frac{L}{h}\right)$$

From the above equation, it can be seen that the maximum normal stress in the beam decreases with decreasing L=h ratio and the maximum shear stress (at the neutral axis) is not affected by the L =h ratio. Thus, for sufficiently small L=h ratios, the maximum shear stress in the beam will reach the ILSS of the material even though the maximum normal stress is still quite low. Thus, the beam will fail in the interlaminar shear mode by cracking along a horizontal plane between the laminas as shown in the below figure.



The recommended L=h ratios for short beam shear tests are between 4 and 5. However, testing a few specimens at various L =h ratios is usually needed before the proper L =h ratio for interlaminar shear failure is found. For very small L=h ratios a compressive failure may occur on the top surface of the specimen, whereas for large L=h ratios a tensile failure may occur at the bottom surface of the specimen. Knowing the maximum load at failure, the IL SS is determined using below equation.

$$\text{Maximum shear stress } \tau_{xz} = \frac{3P}{4bh}$$

Because of its simplicity, the short-beam shear test is widely accepted for material screening and quality control purposes

IMPACT PROPERTIES

The impact properties of a material represent its capacity to absorb and dissipate energies under impact or shock loading (1). Composite materials (3) are often used in environments in which they will suffer from impact damage. For example, damage can occur from a hammer being dropped on a composite pipe or from a bullet striking composite armor. Impact testing fits into two main categories:

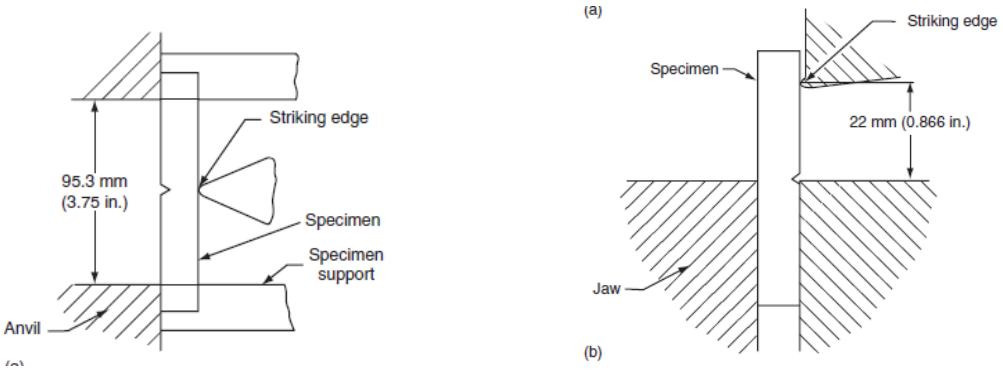
- low velocity impact, and
- high velocity impact.

These two main categories lead to three main types of impact testing.

1. Charpy and Izod impact testing and
2. Drop weight impact testing - low velocity impact testing ASTM D 3763
3. Ballistics impact testing - high velocity impact testing.

Charpy Impact Testing (1)

Charpy and Izod impact tests are performed on commercially available machines in which a pendulum hammer is released from a standard height to contact a beam specimen (either notched or unnotched) with a specified kinetic energy. A horizontal simply supported beam specimen is used in the Charpy test (below figure), whereas a vertical cantilever beam specimen is used in the Izod test (below figure). The energy absorbed in breaking the specimen, usually indicated by the position of a pointer on a calibrated dial attached to the testing machine, is equal to the difference between the energy of the pendulum hammer at the instant of impact and the energy remaining in the pendulum hammer after breaking the specimen.



Schematic arrangements for (a) Charpy and (b) Izod impact tests

Specimen Preparation (3)

The specimen that fits into the Charpy impact tester is rectangular with a notch cut in one side. The notch allows for a predetermined crack initiation location. Many composite Charpy impact tests are performed without the notch cut into the specimen. A typical Charpy impact specimen is shown in the following figure.

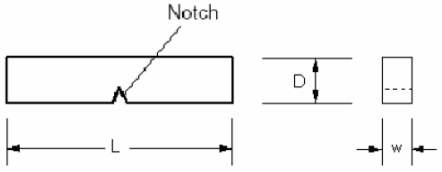


Figure 6.2
Charpy impact specimen

For a typical fiber reinforced polymer Charpy specimen, L = 126 ± 1 mm, D = 12.7 ± 0.15 mm, and 3.00 mm < w < 12.7 mm.

Test Setup and Procedure

Charpy impact test method works by placing a notched specimen (with the notch facing away from the point of contact) into a large machine with a pendulum of a known weight. The pendulum is raised to a known height and allowed to fall. As the pendulum swings, it impacts and breaks the specimen, rising to a measured height. A figure displaying the process is shown below.

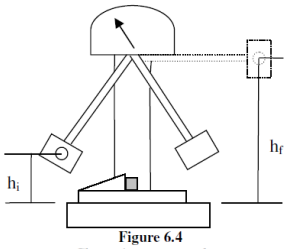


Figure 6.4
Charpy impact procedure

The difference in the initial and final heights is directly proportional to the amount of energy lost due to fracturing the specimen. The total energy of fracture is determined by

$$\Gamma_{total} = mg(h_o - h_f)$$

where

T_{total} is the total energy,

m is the mass,

g is gravitational acceleration,

h_o is the original height, and

h_f is the final height.

The failure types for composite Charpy impact tests depend on the specimen orientation. Often, specimens exhibit fiber fracture and fiber pull-out, while other times delamination failure is the primary failure mode. Examples of post fracture Charpy impact specimens with different failure modes are shown below.

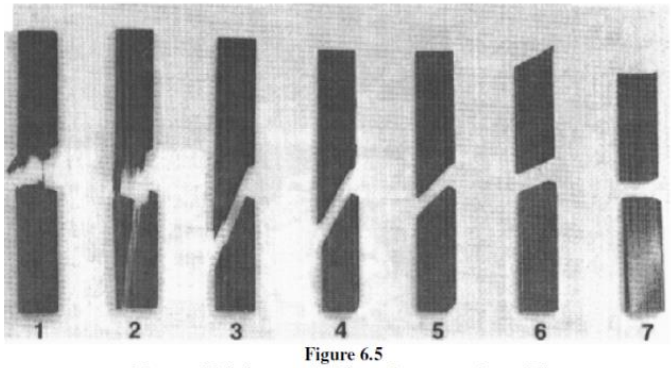


Figure 6.5
Picture of failed composite Charpy impact specimens [6].

Specimens were tested with lay-up angles of 0, 10, 22.5, 30, 45, 67.5, and 90 degrees (from left to right in Figure 6.5). It is possible to see that specimen 1 failed from fiber breakage and pull-out. Specimen 2 failed from a combination of fiber pull-out and fiber-matrix separation, and specimens 3-7 failed at the fiber-matrix interface. Composites therefore may need to be tested in different fiber directions due to the anisotropy of the material. The failure type is important when characterizing composites.

Drop Weight Impact Testing ASTM D 5628

For all low velocity instrumented impact test devices there are three major components:

1. the dynamic load cell (or tup),
2. the data display system, and
3. the signal conditioning unit.

Drop weight impact testing is another type of low velocity testing, and it is the most common test for composite materials. Drop weight impact tests are done to test the impact behavior on composite plates, which most closely resemble impact damage in the field. When using a drop weight impact tester, two categories of damage can occur. The first is **clearly visible impact damage** (CVID), which can easily be seen by the naked eye. The second type of damage is **barely visible impact damage** (BVID), which can seldom be seen by the naked eye. Evaluation of both types of damage can be enhanced through the use of post-impact testing.

Test Principle

In drop weight impact testing, a mass is raised to a known height and released, impacting the specimen. The choice can be made between either an instrumented or non-instrumented test machine. A figure displaying how an instrumented impact machine works is shown below.

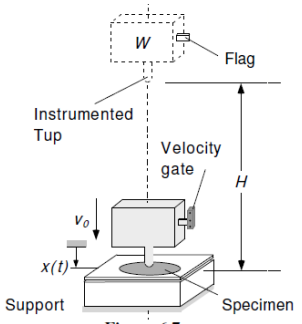


Figure 6.7
Example of the operation of a drop weight impact test machine

In the above figure, *x(t)* is the coordinate system, *H* is the initial drop height, *W* is the impact weight, and *v*o is the impact velocity. The tup is a hemispherical impactor that measures the strain during impact.

Specimen Preparation and Test Setup

The specimens used for drop weight testing are flat panel composite specimens. The lay-up and material used is dependent on the desired results of the testing. The flat panel specimen preparation is similar to that of the panels used in the Charpy impact test. Following the creation of the panel, specimens are cut to the desired size. This flat specimen is then inserted into the test machine and clamped along its edges. The clamps can be placed in a circumferential configuration or in a rectangular configuration, based on the design and test specifications (a common standard is ASTM D 5628). Once the test specimen is clamped down, the mass is raised to the desired height, and the mass is locked into place.

Test Procedure and Data Evaluation

Once the machine is set to its correct configuration and all data acquisition software is running, the mass is released and allowed to impact the plate. A picture of an impacted test specimen is shown in the following figure.

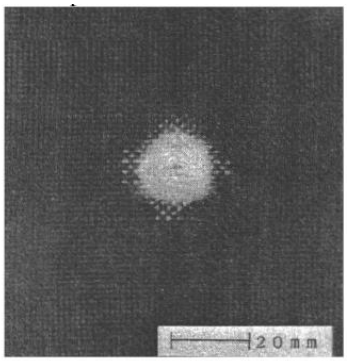


Figure 6.9
Post impact drop weight test specimen [11].

The strains measured by the tup are loaded into a software program, and the data obtained from the test can be examined to see the impact resistance of the plate. The data is plotted as **force, energy, or displacement vs. time**. The data, however, is not always conclusive and often post-impact analysis is required. A graph of a typical instrumented impact test is shown below. The graph shown in Figure 6.10 gives information about how the material behaves during the impact process. The load drops upon fracture initiation. In order to gain more information, the impacted sample is often analyzed using post-impact analysis techniques. Post-impact testing

can determine the amount of strength left before ultimate failure, or examine the failure mode of the specimen after it has been impacted.

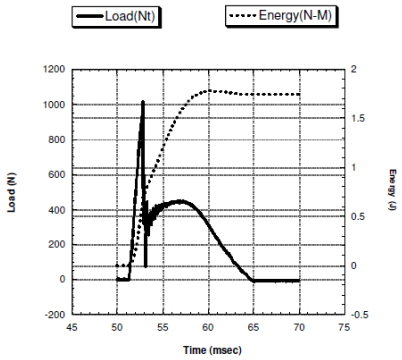


Figure 6.10
Example plot of force vs. time curve for drop weight impact test.

High Velocity Impact Test

Ballistics Testing

Ballistics testing is a form of high speed testing that is used to test the ultimate impact strength of composites. High velocity testing is characterized by an impactor traveling in the range of **400-2000 m/s**. For high velocity impact conditions, structural response is less important than in a low velocity case, and the damage area is more localized; therefore the geometrical considerations are less important.

Principle

Ballistics testing consists of firing a high speed projectile at an object and determining after the impact how localized the damage is. This is a good method for testing impact resistance of composites, and has been used for testing products such as composite armor.

Test Setup and Procedure

Ballistics testing is complicated, and care has to be taken during the setup. A typical setup of a conventional ballistics test apparatus is shown in the following figure.

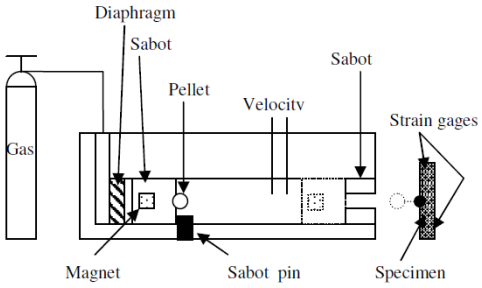


Figure 6.11
Apparatus for ballistic impact testing

The test apparatus shown in the above figure is typically known as a gas-gun impact test machine. The gas-gun apparatus works by forcing gas into the back of the

diaphragm which expands and applies pressure to the sabot. The sabot pin is released, and the sabot is forced along the barrel. The velocity pins measure the time it takes for the front of the sabot to travel the distance between the two pins, and outputs a velocity. The sabot is then blocked by the sabot stops, and the pellet is allowed to proceed to impact the test specimen. The strains can then be measured using strain gages applied to the specimen. The pellet used for testing is usually one with a high hardness, and will be made of a hard steel, or zirconia (for the setup shown in the above figure, the pellet would have to be magnetic, as it is held in place by a magnet). An inert gas is used to fill the chamber to cut down on possible accidents.

Data Evaluation

When performing ballistics testing, data evaluation often has to be accompanied by a different method for defining the damage done. There are different ways to analyze post impact damage. When doing calculations for ballistics testing, some assumptions must be made.

1. One assumption is that the velocity of the pellet remains constant from the time that it is measured with the velocity pins until the time that it contacts the specimen.
2. The second is that the energy lost from the pellet is proportional to the energy absorbed by the specimen.

The remaining energy of the pellet can be measured using sensors to detect its rebound velocity (or in the case of a through laminar failure its remaining velocity). When calculating the necessary unknowns that come with ballistics testing, the equations can become rather complex.

FAILURE MODES IN IMPACT TEST (2)

Impact behaviors and impact damages depend on many parameters such as the

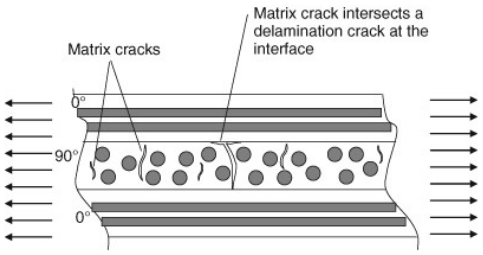
1. projectile/impactor shape,
2. impact velocity and energy,
3. boundary conditions and
4. lay-up sequence.

Furthermore, laminated fibre reinforced composite materials have various damage modes such as

1. fibre breakage,
2. matrix cracking, and
3. delamination.

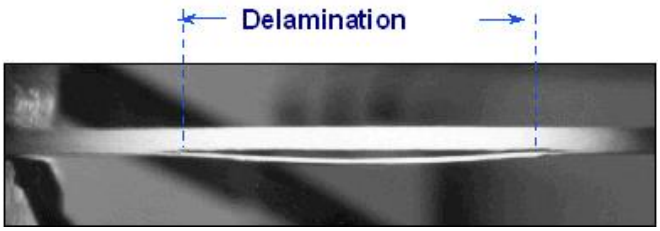
Matrix cracking

Matrix cracking is the first type of failure, usually caused by low-velocity impact and occurs parallel to the fibres due to tension, compression and shearing. Shear cracking (inclination of 45^{o}) and bending cracking (vertical inclination) are examples of matrix cracking. It is the first damage that affects the structure but cannot be seen by naked eye. It can decrease the interlaminar shear and compression strength properties on the resin or the fibre/resin interface. Micro-cracking can have a very negative effect on a high temperature resin's properties.



Delamination

In a low velocity impact, the most critical damage mechanism in composites is delamination. Delaminations form between the layers in the laminate. It may be initiated by matrix cracks when the threshold energy has been reached or from low energy impact. Delamination can dramatically reduce the post-impact compressive strength of the laminate.



Fibre Failure

Fibre pull out and fibre breakage are the most common failures under low velocity impact testing. Fibre failure occurs because of the high stress field and indentation

effects. The projectile induces a shear force and high bending stresses in the non-impacted side of the specimen.

Test Methods for Post Impact Damage Testing - Residual Strength After Impact **(1)**

If a composite laminate does not completely fail by impact loading, it may still be able to carry loads even though it has sustained internal as well as surface damages. The load-carrying capacity of an impact-damaged laminate is measured by testing it for residual strength in a uniaxial tension test. The postimpact residual strength as well as the damage growth with increasing impact velocity is shown in the below figure.

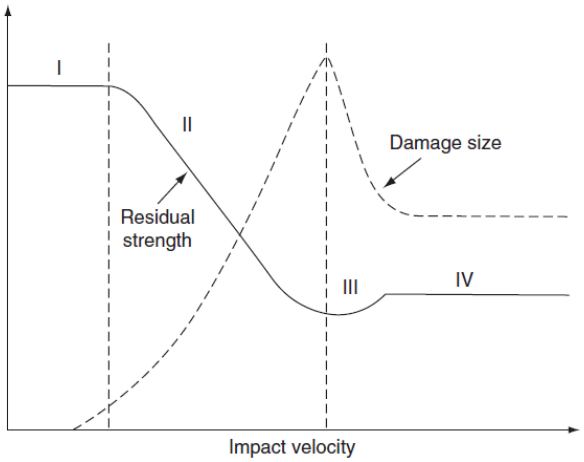
For small impact velocities, no strength degradation is observed (region I). As the damage appears, the residual tensile strength is reduced with increasing impact velocity (region II) until a minimum value is reached just before complete perforation (region III). Higher impact velocities produce complete perforation, and the hole diameter becomes practically independent of impact velocity (region IV). The residual strength in this region remains constant and is equal to the notched tensile strength of the laminate containing a hole of the same diameter as the impacting ball. Husman et al. proposed the following relationship between the residual tensile strength in region II and the input kinetic energy:

$$\sigma_R = \sigma_U \sqrt{\frac{U_s - k U_{KE}}{U_s}}$$

where

σ_R = residual tensile strength after impact

σ_U = tensile strength of an undamaged laminate



Schematic representation of the residual static strength in impact damaged laminates.

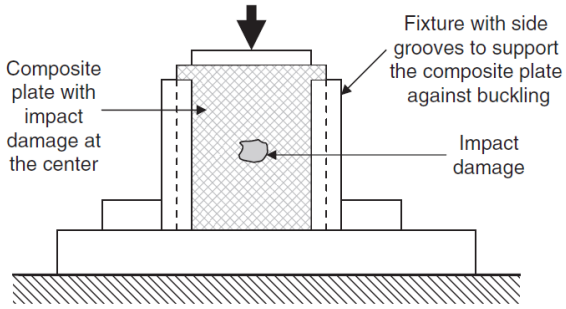
Us = area unde r the stress–s train curve for an undamaged laminate

UKE = input kinetic energy per unit laminate thickness

k = a constant that depends on the laminate stacking sequence and boundary conditions (e.g., one end fixed vs. both ends fixed)

COMPRESSION AFTER IMPACT T EST (CAI)

The compression- after-impact test is used for assessing the nonvisible or barely visible impact damage in composite laminates. An edge-supported quasi isotropic laminated plate, 153 mm X 102 mm X 3–5 mm thick, is impacted at the center with an energy level of 6.7 J/mm. After nondestructively examining the extent of impact damage (e.g., by ultrasonic C-scan) , the plate is compression tested in a fixture with antibuckling guides (below figure) .



Test fixture for compression test after impact

The compressive strength of an impact damaged laminate is lower than the undamaged compressive strength.

Failure modes observed in compression after impact tests are shear crippling of fibers and ply delamination. In brittle epoxy laminates, delamination is the predominant failure mode, while in toughened epoxy matrix composites, significant

shear crippling occurs before failure by ply delamination. Post impact compressive strength (PICS) of a laminate can be improved by reducing the impact-induced delamination. One way of achieving this is by increasing the interlaminar fracture toughness of the laminate.

MATERIAL PARAMETERS

The primary factor influencing the impact energy of a unidirectional 0° composite is the fiber type. Increasing the fiber volume fraction also leads to higher impact energy. The next important factor influencing the impact energy is the fiber–matrix interfacial shear strength. Several investigators have reported that impact energy is reduced when fibers are surface treated for improved adhesion with the matrix. At high levels of adhesion, the failure mode is brittle and relatively little energy is absorbed. At very low levels of adhesion, multiple delamination may occur without significant fiber failure. Although the energy absorption is high, failure may take place catastrophically. At intermediate levels of adhesion, progressive delamination occurs, which in turn produces a high impact energy absorption. Different coupling agents were used on E- glass woven fabrics to achieve various ILSSs in short-beam shear tests. It was observed that the fracture initiation energy increases modestly with increasing ILSS. However, the fracture propagation energy as well as the total impact energy decrease with increasing ILSS, exhibit a minimum, and appear to level off to intermediate values. The principal failure mode at low ILSSs was delamination. At very high ILSSs, fiber failure was predominant. In unidirectional composites, the greatest impact energy is exhibited when the fibers are oriented in the direction of the maximum stress, that is, at 0° fiber orientation. Any variation from this orientation reduces the load carrying capacity as well as the impact energy of the composite laminate. Furthermore, fracture in off-axis specimens took place principally by interfiber cleavage parallel to the fiber direction in each layer. The most efficient way of improving the impact energy of a low strain to failure fiber composite is to hybridize it with high strain-to-failure fiber laminas.

ENVIRONMENTAL EFFECTS

The influence of environmental factors, such as elevated temperatures, high humidity, corrosive fluids, and ultraviolet (UV) rays, on the performance of polymer matrix composites is of concern in many applications. These environmental

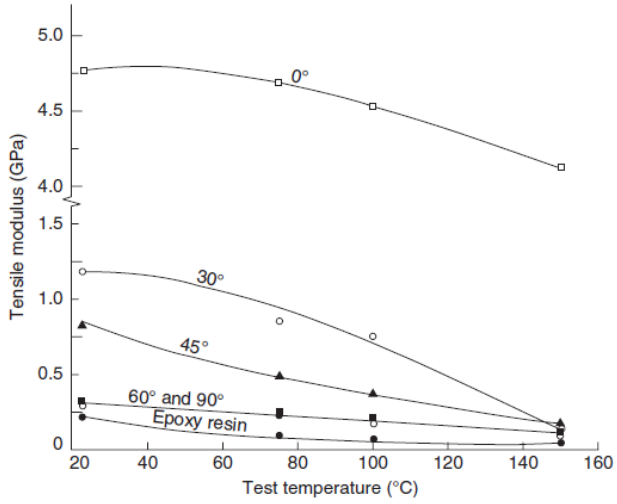
conditions may cause degradation in the mechanical and physical properties of a fiber-reinforced polymer because of one or more of the following reasons:

1. *Physical and chemical degradation of the polymer matrix, for example, reduction in modulus due to increasing temperature, volumetric expansion due to moisture absorption, and scission or alteration of polymer molecules due to chemical attack or ultraviolet rays. However, it is important to note that different groups of polymers or even different molecular configurations within the same group of polymers would respond differently to the same environment.*
2. *Loss of adhesion or debonding at the fiber–matrix interface, which may be followed by diffusion of water or other fluids into this area. In turn, this may cause a reduction in fiber strength due to stress corrosion.* (Many experimental studies have shown that compatible coupling agents are capable of either slowing down or preventing the debonding process even under severe environmental conditions, such as exposure to boiling water).
3. *Reduction in fiber strength and modulus. For a short-term or intermittent temperature rise up to 150°C–300°C, reduction in the properties of most commercial fibers is insignificant. However, depending on the fiber type, other environmental conditions may cause deterioration in fiber properties. For example, moisture is known to accelerate the static fatigue in glass fibers. Kevlar fibers are capable of absorbing moisture from the environment, which reduces its tensile strength and modulus. The tensile strength of Kevlar fibers is also reduced with direct exposure to ultraviolet rays.*

ELEVATED TEMPERATURE TEST

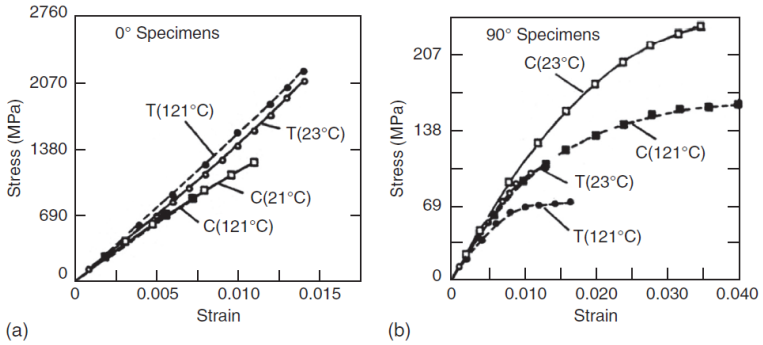
When a polymer specimen is tension-tested at elevated temperatures, its modulus and strength decrease with increasing temperature because of thermal softening. In a polymeric matrix composite, the matrix dominated properties are more affected by increasing temperature than the fiber dominated properties. For example, the longitudinal strength and modulus of a unidirectional 0° laminate remain virtually unaltered with increasing temperature, but its transverse and off-axis properties are significantly reduced as the temperature approaches the T_g of the polymer. For a randomly oriented discontinuous fiber composite, strength and modulus are reduced in all directions. Reductions in modulus as a function of increasing test temperature are shown for unidirectional continuous and randomly oriented discontinuous fiber laminates in the below figures. Thermal aging due to long-term

exposure to elevated temperatures without load can cause deterioration in the properties of a polymer matrix composite.



Effect of increasing test temperature on the static tensile modulus of unidirectional E-glass–epoxy laminates.

The concern for the reduction in mechanical properties of thermoplastic matrix composites at elevated temperatures is more than the thermoset matrix composites, since the properties of thermoplastic polymers reduce significantly at or slightly above their glass transition temperatures. As in thermoset matrix composites, the effect of increasing temperature is more pronounced for matrix dominated properties than for fiber dominated properties as shown in below figure.



Tensile (T) and compressive (C) stress–strain diagrams of 0° and 90° carbon fiber-reinforced PEEK laminates at 23°Cand121°C.

FIBER CONTENT, DENSITY, AND VOID CONTENT

Theoretical calculations for strength, modulus, and other properties of a fiber reinforced composite are based on the fiber volume fraction in the material. Experimentally, it is easier to determine the fiber weight fraction w_f, from which the fiber volume fraction v_f and composite density ρ_c can be calculated:

$$v_f = \frac{w_f/\rho_f}{(w_f/\rho_f) + (w_m/\rho_m)}$$

$$\rho_c = \frac{1}{(w_f/\rho_f) + (w_m/\rho_m)}$$

Where,

w_f = fiber weight fraction (same as the fiber mass fraction)

w_m = matrix weight fraction (same as the matrix mass fraction) and is equal to (1_w_f)

r_f = fiber density

r_m = matrix density

In terms of volume fractions, the composite density rc can be written as

$$\rho_c = \rho_f v_f + \rho_m v_m$$

Where,

v_f is the fiber volume fraction and v_m is the matrix volume fraction. Note that v_m is equal to (1_v_f).

The fiber weight fraction can be experimentally determined by either the ignition loss method (ASTM D2854) or the matrix digestion method (ASTM D3171). The ignition loss method is used for PMC-containing fibers that do not lose weight at high temperatures, such as glass fibers. In this method, the cured resin is burned off from a small test sample at 500°C–600°C in a muffle furnace.

In the matrix digestion method, the matrix (either polymeric or metallic) is dissolved away in a suitable liquid medium, such as concentrated nitric acid. In both cases, the fiber weight fraction is determined by comparing the weights of the test sample before and after the removal of the matrix. For unidirectional composites containing electrically conductive fibers (such as carbon) in a nonconductive matrix, the fiber volume fraction can be determined directly by comparing the electrical resistivity of the compo site with that of fibers (ASTM D3355). During the incorporation of fibers into the matrix or during the manufacturing of laminates, air or other volatiles may be trapped in the material. The trapped air or volatiles exist in the laminate as microvoids, which may significantly affect some of its mechanical properties. A high void content (over 2% by volume) usually leads to lower fatigue resistance, greater susceptibility to water diffusion, and increased variation (scatter) in mechanical properties. The void content in a composite laminate can be estimated by comparing the theoretical density with its actual density:

$$v_v = \frac{\rho_c - \rho}{\rho_c}$$

Where,

V_v = volume fraction of voids

ρ_c = theoretical density, calculated from Equation 2.8 or 2.9

ρ = actual density, measured experimentally on composite specimens (which is less than ρ_c due to the presence of voids)

EXAMPLE 2.1

Calculate v_f and ρ_c for a composite laminate containing 30 wt% of E-glass fibers in a polyester resin. Assume $\rho_f = 2.54$ g/cm^3 and $\rho_m = 1.1$ g/cm^3.

SOLUTION

Assume a small composite sample of mass 1 g and calculate its volume.

	Fiber	Matrix
Mass (g)	0.3	$1 - 0.3 = 0.7$
Density (g/cm^3)	2.54	1.1
Volume (cm^3)	$\frac{0.3}{2.54} = 0.118$	$\frac{0.7}{1.1} = 0.636$

Therefore, volume of 1 g of composite is (0.118 + 0.636) or 0.754 cm^3. Now, we calculate

Fiber volume fraction $v_f = \frac{0.118}{0.754} = 0.156$ or 15.6%

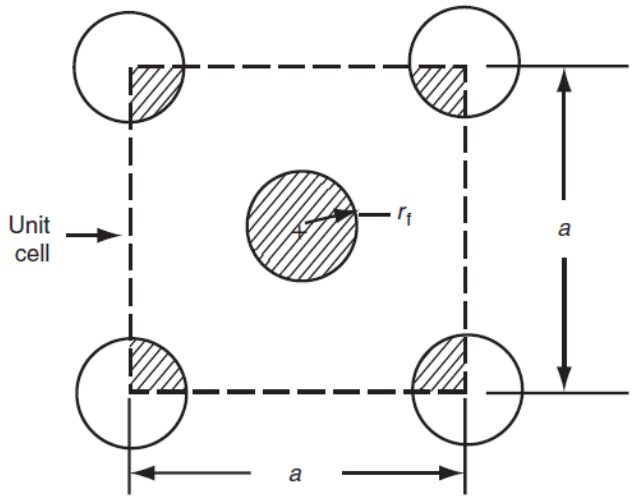
Matrix volume fraction $v_m = 1 - v_f = 1 - 0.156 = 0.844$ or 84.4%

$$\text{Composite density } \rho_c = \frac{1 \text{ g}}{0.754 \text{ cm}^3} = 1.326 \text{ g/cm}^3$$

Note: These values can also be obtained using Equations 2.7 and 2.8.

EXAMPLE 2.2

Assume that the fibers in a composite lamina are arranged in a square array as shown in the figure. Determine the maximum fiber volume fraction that can be packed in this arrangement.



SOLUTION

Number of fibers in the unit cell = 1 + (4) (1/4) = 2
Fiber cross-sectional area in the unit cell = (2) (πr_f^2)
Unit cell area = a^2
Therefore,
Fiber volume fraction (v_f) = $\dfrac{2\pi r_f^2}{a^2}$
from which, we can write

$$a = \frac{\sqrt{2\pi}}{v_f^{1/2}} r_f.$$

Interfiber spacing (R) between the central fiber and each corner fiber is given by

$$R = \frac{a}{\sqrt{2}} - 2r_f = r_f\left[\left(\frac{\pi}{v_f}\right)^{1/2} - 2\right].$$

For maximum volume fraction, $R = 0$, which gives

$$v_{f_{max}} = 0.785 \text{ or } 78.5\%.$$

References:

1. P.K. Mallick, "Fiber reinforced composites, Materials, Manufacturing and Design", CRC Press, 2008.
2. S.N.A. Safri, “Low Velocity and High Velocity Impact Test on Composite Materials – A review”, The International Journal Of Engineering And Science (IJES), Volume 3, issue 9, pages 50-60, 2014.
3. Joshua M. Duell, "Impact Testing of Advanced Composites "