# 7
# Mechanical Property Measurement

## 7.1 Introduction

Mechanical testing of materials and structural details is conducted to satisfy one or more of the following objectives: 1) characterization of materials or processes, 2) development of design allowables, 3) qualification of materials for certain applications, 4) quality control, 5) assessment of strength and durability under sustained or cyclic loads, or 6) assessment of the influence of damage or degradation on residual strength.

Aerospace wrought metal alloys are available in standard pre-fabricated forms with well-characterized properties. By contrast, composites are usually formed at the same time as the component is manufactured and therefore can have a very wide range of properties depending on the fiber, resin, lay-up, volume fraction, etc. Some properties of composites are more sensitive to environmental conditions. Thus, testing requirements are generally more demanding than is the case for metals.

The use of mechanical testing for developing design allowables for composites is described in Chapter 13, and its use in the testing of adhesively bonded or mechanically fastened joints is described in Chapter 9.

### *7.1.1 Types of Mechanical Tests*

Most tests are conducted under static tensile, compressive, or shear loading. They may also be conducted under flexural loading, which induce tensile, compressive, and shear stresses in the various zones of the specimen. The static loading may be of short duration, taking only a few minutes, as in a standard tensile test to measure strength or stiffness.

Static tests, most generally performed under tensile loading, may be also be prolonged for weeks or months, as in a creep test, to measure the long-term strength and strain stability—often at elevated temperature. These tests are usually conducted at various percentages of the short-term ultimate tensile strength, typically 10–50%.

Cyclic loading tests to measure resistance to degradation and cracking under varying loads are essentially repeated static loading.[1] The frequency of application is generally low, in the case of composites around 5–10 Hz, to avoid heating. Loading may be tension/tension, tension/compression, or reversed shear at constant amplitude or under spectrum loading, and may be aimed at simulating the actual loading conditions in a particular application.

Dynamic loads are used to measure the resistance of the materials to impact or ballistic conditions. These tests are also conducted under tension, compression, shear, or flexure, or they may be conducted using an impactor or penetrator of some type. In some tests, the impact event may occur while the specimen is under tensile or compressive loading. Typically, loading occurs over a 1-millisecond time interval.

Testing may be conducted at different temperatures and levels of absorbed moisture. They may also include exposure to a range of other environmental conditions, such as UV and solvents.

The specimens may be simple coupons or they may be structural details with representative stress-raisers such as holes, filled with a fastener or open. The coupons or details may include representative damage such as sharp notches or impact damage.

Test machines consist of loading frames, one fixed and one moving crosshead, separated either by a simple electromechanical screw action or by a servo-hydraulic piston. For simple static testing, the screw-driven machines are simpler and less costly and there is less danger of overload caused by accidental rapid movement of the crosshead. However, for versatility in loading (e.g. spectrum loading in fatigue testing) and in load capacity, the servo-hydraulic machines are unmatched.

### 7.1.2 Special Requirements for Testing Composites

During the early development of composites, many of the test techniques used for metals and other homogenous, isotropic materials were used to determine the properties of composite materials. It was soon recognized that anisotropic composite materials often required special consideration in terms of mechanical property determination. Much of the test method development was also undertaken within individual organizations, thus standardization was difficult and many methods developed were not adequate for the newer, emerging materials.

Since those early days, there has been a great deal of effort devoted to the standardization of test methods, and there are a number of reference sources that can be used to identify the relevant techniques. Test standards have been published by the American Society for Testing and Materials (ASTM)[2–9] and the Suppliers of Advanced Composite Materials Association (SACMA),[10,11] together with other information sources such as the U.S. Department of Defense Military Handbook 17 (MIL-HDBK 17; Polymer Matrix Composites). MIL-HDBK 17 is specifically suited to composite materials for aerospace applications and is generally used for test method selection.

The test techniques briefly described here are the ones most commonly used when measuring stress and strain in the tensile, compressive, flexural, and shear load states, but they are not the only techniques that can be used. The most critical issues that must be satisfied are that the test method used accurately creates the required stress state in the material and that the specimen failure be consistent with this stress state and not be artificially influenced by the test method.

Because of the variabilties encountered in coupon testing, airworthiness authorities require multiple tests across several batches. MIL-HDBK 17 recommends a minimum of six specimens per test point and five batches of material to be tested. These requirements mean that the exploration of even a minimum of material properties entails a very large number of test specimens.

When conducting tests to determine the strength and stiffness of a composite material, the first question that must be answered is "What mode of its performance is to be measured?" Composites, as with other materials, can have significantly different mechanical properties when tested in different ways. The main loading modes that are generally of interest are tension, compression, flexure, and shear—each has its own particular test techniques and difficulties.

To facilitate design computations, the elastic properties of the composite lamina discussed in Chapter 6 are usually obtained first through simple coupon tests. Recall the relationships for in-plane elastic properties, noting that in most cases, in-plane properties will be used to design the laminate:

$$\begin{vmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{vmatrix} = \begin{vmatrix} 1/E_1 & -\nu_{12}/E_2 & 0 \\ -\nu_{12}/E_1 & 1/E_2 & 0 \\ 0 & 0 & 1/G_{12} \end{vmatrix} \begin{vmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{vmatrix}$$

And since $\nu_{12}/E_1 = \nu_{21}/E_2$ (See Chapter 6), only three tests are required to establish the in-plane elastic properties, in other words, 0° tension, 90° tension, and in-plane shear.

Because it is not possible to conduct tests on single plies, the coupons are laid up with multiple plies, all orientated in the same direction. The exception is the in-plane shear in which, if a 45° tension test is selected (see below), plies are alternated between + and −45° symmetric about the center line.

Strength values should not, in general, be taken from these coupons although they are very often taken to failure. The reasons for this are explained in Chapter 12. Laminate strength should be obtained from tests on representative laminates in which the orientations of the fiber lay-up are similar to those anticipated in the design. These values that are used in initial design are generally substantiated by tests on structural elements and often finally on full-scale structures. This is often referred to as the Testing Pyramid, which is illustrated in Figure 7.1.

It must be understood that issues such as scale effects[12] and complex load conditions[13] can become important when testing composite components, and the data obtained from simple coupon tests can often only be used for comparing materials and not as accurate predictions of component behavior.

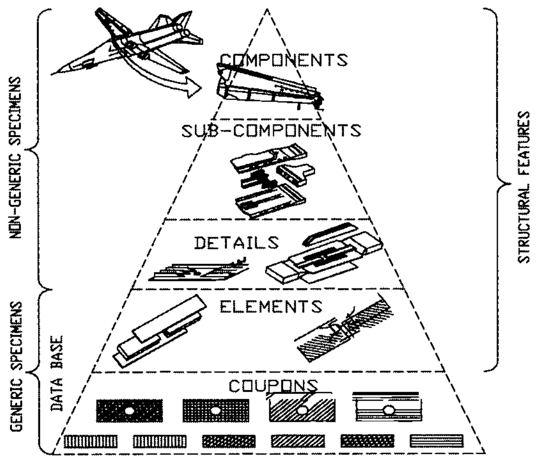



**Fig. 7.1 Testing pyramid for composite structures.**

## 7.2 Coupon Tests

### *7.2.1 Tension*

Valid axial tension testing, particularly of strong unidirectional composites, can be a challenge. The load must be transferred from the testing apparatus into the specimen via shear, and the shear strengths of composites are often significantly lower than their tensile strength. Thus shear failure within the gripping region is often a problem.

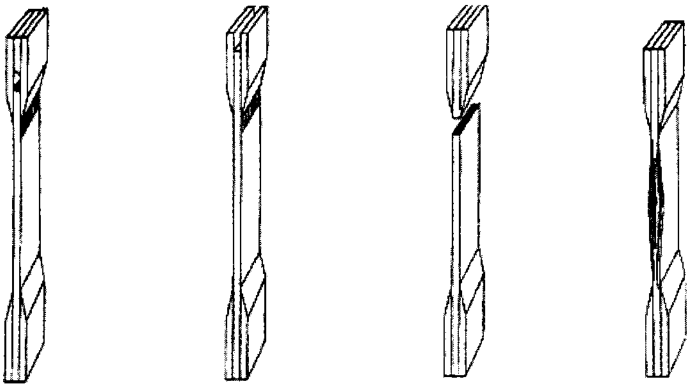
The standard test technique (outlined in Refs. 2 and 3 for open-hole tension) describes the use of a parallel-sided, rectangular specimen with bonded end tabs. However, these tabs, which are normally made from a glass fabric/epoxy composite, are not strictly required. The key factor is the successful introduction of load into the specimen. Therefore, if acceptable failures are being obtained with reasonable consistency, then it can be assumed that the gripping method is working. A wide variety of bonded tab or unbonded shim configurations have been used successfully. One unbonded shim material sometimes used is a coarse mesh made of carborundum-coated cloth.

Load measurement is performed via the load cell in the test machine, and strain measurement is done by an extensometer secured to the specimen or by adhesively bonded strain gauges. To measure Poisson's ratio, both the axial and transverse strain must be measured concurrently. Extensometers are normally preferred because they are reusable, easier to mount, and often more reliable at elevated temperatures or in high-moisture-content environments. If strain gauges are used, then the active gauge length (length of specimen over which the strain is measured) is recommended to be at least 6 mm for tape composites and at least as large as the characteristic repeating unit of the weave for woven materials.

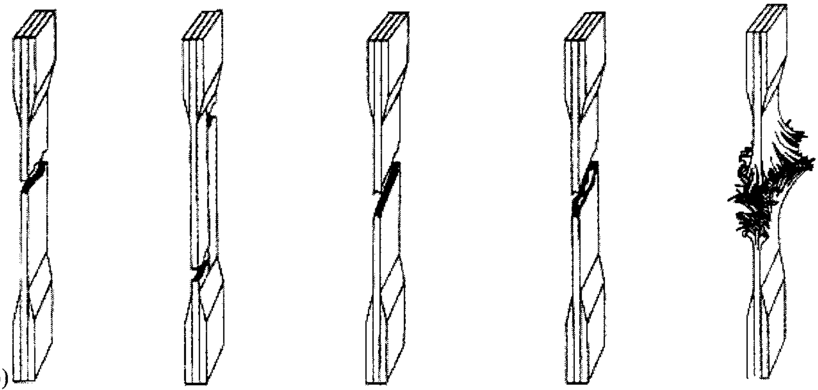
A successful test must cause failure within the gauge region. Failure at the tab edge (or gripped edge) or within the tab is unacceptable. Failure due to early edge delamination, which is normally caused by poor machining, is also unacceptable. Figure 7.2 illustrates typically a) unacceptable and b) acceptable specimen failures. Poor load system alignment is often a major contributor to premature failure, and it is highly desirable to evaluate system alignment with a suitably strain-gauged, alignment coupon.

### 7.2.2 Compression

There is still a great amount of debate among researchers as to the most appropriate method for compression testing or indeed whether there is a true axial compression test for composites.[14,15] Generally, compression failure occurs through buckling, ranging from classical column buckling of the entire specimen



a)



b)

**Fig. 7.2 Failure modes in tensile testing: *a*) unacceptable; *b*) acceptable.**

cross-section to local microbuckling of fibers that often leads to failure through the process of kink band formation.[4] Therefore, the greater resistance to buckling the test fixture provides to the specimen, the higher the value of compressive strength that is obtained.

Many different test methods and specimen configurations have been developed over the decades in an attempt to limit specimen buckling, and there are a number of tests that have become the most widely used in current practice. The Illinois Institute of Technology Research Institute (IITRI) method,[4] which has become an ASTM standard, and the modified ASTM D695 method[10] (currently a SACMA standard), are two methods used for un-notched specimens (Figs. 7.3 and 7.4, respectively). The SACMA Recommended Test Method 3R-94[11] is commonly used for open-hole compression testing Fig. 7.5.

As with the tension test, tabs are not absolutely required for the specimen, although they are strongly recommended for specimens made with unidirectional reinforcement. The main criteria is that correct failure occurs within the gauge

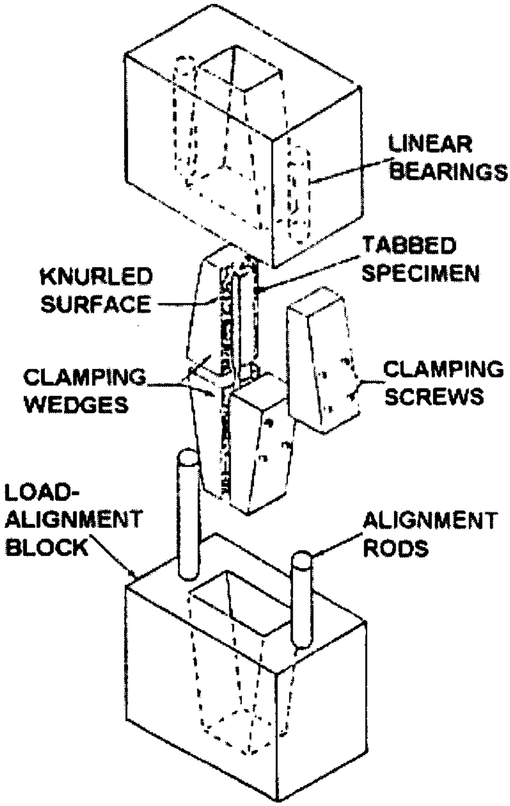



**Fig. 7.3 The IITRI compression test rig.**

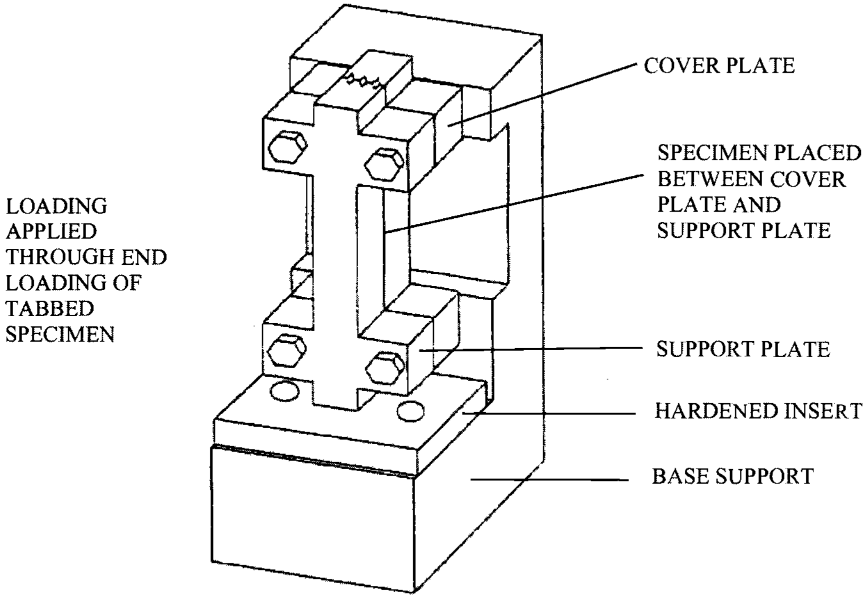



**Fig. 7.4 Modified ASTM D695 compression test rig.**

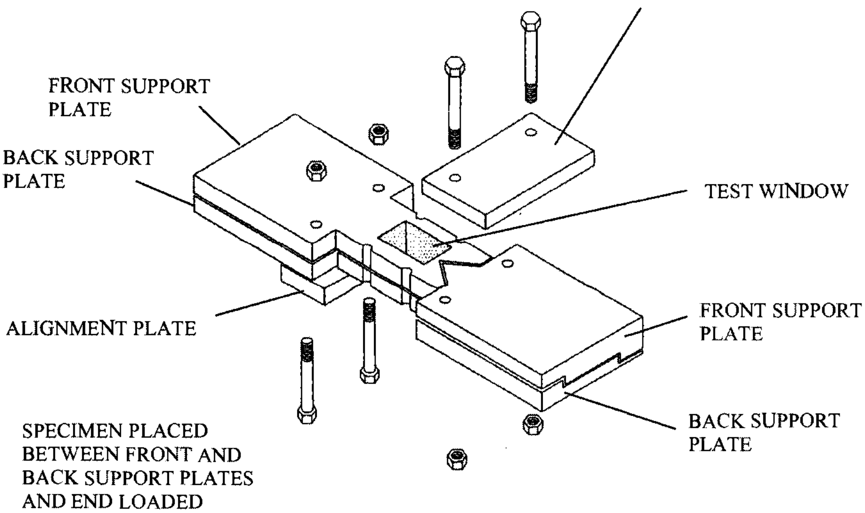


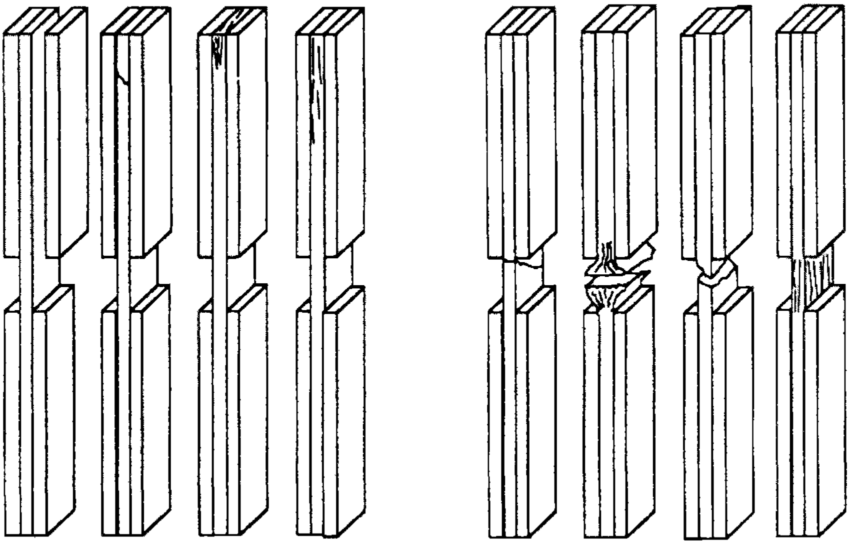

**Fig. 7.5 Rig for the SACMA recommended test method 3R-94 for open-hole compression testing.**

area; if this does not occur correctly, then the data point should not be used. Figure 7.6 illustrates examples of acceptable and unacceptable failures, with any failure residing solely in the tabbed or gripped region being considered unacceptable. Due to the very short gauge length, it is likely that the failure location could be near the grip/tab termination region; this is still an acceptable failure.

Compression tests are very sensitive to the flatness and parallelism of the specimens and/or tabs, and within the test specifications, the required tolerances are outlined. Gripping of the specimens and system misalignment are generally the biggest cause of data scatter, and of particular relevance to the test methods that use stabilizing lateral supports (SACMA SRM 1R-94 and 3R-94) is the issue of bolt torque. An over-torque of the bolts allows more of the applied load to be carried by the lateral supports through friction, thereby increasing the apparent compressive strength. Generally, the bolts are tightened up to a "finger-tight" level, a fairly arbitrary measurement; however studies[15] have shown that the torque should not exceed approximately 1 Nm.

### 7.2.3 Flexure

A flexure test is, without doubt, one of the simplest types of tests to perform and thus has long been popular (Fig. 7.7). The main difficulty is that it does not



a) b)

**Fig. 7.6 Failure modes in compression testing: *a*) unacceptable; *b*) acceptable.**

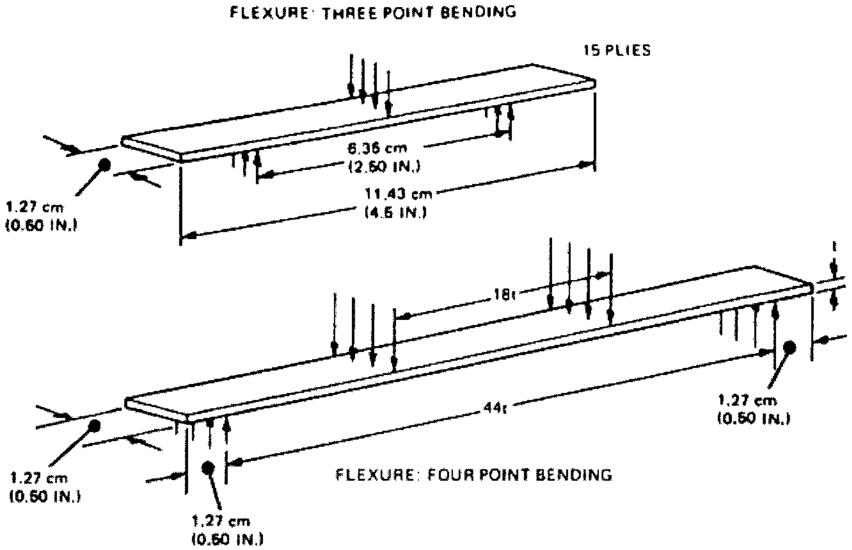



**Fig. 7.7 ASTM test methods for the flexure test.**

provide basic material property information because of the variation in stress-state within the specimen. The stress-state on the loading side is compression and on the supported side is tension; the mid-plane of the specimen is in pure shear. Therefore, depending on the relative values of the tension, compression, and shear strengths of the material, any one of these properties may be measured. The ratio of the support span length to specimen thickness is normally set long enough so that shear failure does not occur (32 : 1 is common) but whether failure initiates on the tensile or compressive face will be dependent on the material.

Although the flexure test does not provide basic design data, its use is normally justified if the actual components are subjected to flexure. This is a valid argument if the span length to thickness ratio is similar to the laboratory test specimens. If not, the failure mode of the component in service may be different, and thus any comparison of the laboratory testing is not valid.

The details of the standard flexure test are contained within the ASTM specification D790–84a[5] and this provides the recommended dimensions and cross-head speeds for various materials. There are two possible test configurations that can be used: three-point bending and four-point bending (Fig. 7.7). Although the three-point bending test requires less material, the four-point bending has the advantage that uniform tensile or compressive stresses (with zero shear) are produced over the area between the loading points, not just under the loading point as in three-point bending test. In the three-point test, the high local stresses at the loading point affects the failure mode and load. It should be noted that excessive bending of the specimen before failure can render the test invalid due to slipping of the specimen over the support points. This situation is discussed within the test specification.

In specimens with sandwich construction having relatively thin skins on a honeycomb (or other suitable) core, loading in flexure simultaneously provides tensile stresses in one skin and compressive stresses in the other. This form of testing is particularly advantageous for compression testing of composites because a much larger area of skin can be tested than is possible in the standard tests, and the loading is far more realistic.

### 7.2.4 Shear

Shear testing of composites is often a cause of confusion. Many different test procedures have been used, and only now are some gaining acceptance. This situation is hampered by the fact that many techniques cannot provide both shear strength and modulus from the one test.

The ideal test for shear is torsion of a thin-walled tube, which provides a pure shear stress-state, yet this method is not often used. The specimens are relatively expensive, fragile, and difficult to hold and align correctly, and the technique requires a torsion-testing machine of sufficient capacity. Currently, the two-rail shear test[6] (Fig. 7.8) and the Iosipescu test[7] (Fig. 7.9) are the most commonly used, although, it should be noted that the rail shear test is currently issued by ASTM as a Standard Guide, not a Standard Method. Both of these tests are not recommended for specimens containing only $\pm 45^\circ$ fibers; rather, these specimens should be tested using the method outlined in Ref. 8, which involves the use of a routine tensile test.

Difficulties can arise when using the rail shear test because the specimens generally fail by out-of-plane buckling, therefore the measured values of strength and strain will be affected. Stress concentrations can also occur at the rail attachments, and suitable design of the rail area is critical to prevent failure occurring here. Due to these problems, shear data obtained using this test is often questioned.

The Iosipescu test, nevertheless, is gaining in popularity due to having none of the disadvantages of the rail shear test and having the added advantages of using much less material and producing an essentially pure shear stress; however, shear stress concentrations develop at the root of the notches. Another advantage is that the test can be used to measure shear properties in any orientation. Thus, the Iosipescu method can be used to provide interlaminar shear properties by machining the specimen so that the interlaminar plane is parallel to the plane of the gauge area. The test specification contains recommendations for dimensions, but it is critical that the gauge area contain a sufficient number of fabric repeat units to ensure material properties are obtained. ASTM gives no guidelines on this but it is generally accepted that a minimum of 3 repeat units are used, therefore the specimen should be scaled up to achieve this. Twisting of the

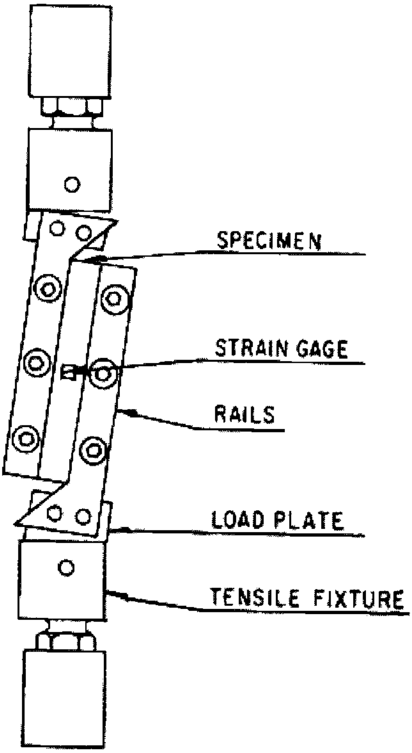



**Fig. 7.8 Two-rail shear test rig.**

specimen can occur during the test, therefore accurate machining (precision grinding or milling techniques) and specimen placement are critical.

The $\pm 45°$ Off-Axis Tensile Shear Test (ASTM D3518) consists of loading a $\pm 45°$ symmetric laminate uniaxially in tension. It is cheap and easy, and good correlation has been obtained with other test methods. It is argued that it provides a value more reflective of the actual stress-state in a laminated structure.

The discussion above relates to in-plane shear testing; however, for laminates there is often the need to measure interlaminar shear properties. This is normally accomplished through the use of a short-beam shear test, such as defined by ASTM D2344,[9] that is, a three-point flexure test of a very short beam (ratio of support span to specimen depth is generally less than 5). It should be noted that, although this test method provides reasonable comparative interlaminar shear strength values, it cannot provide shear stiffness or strain information. MIL-HDBK 17 does not recommend its use for strength prediction, however this is sometimes done on the absence of other data.

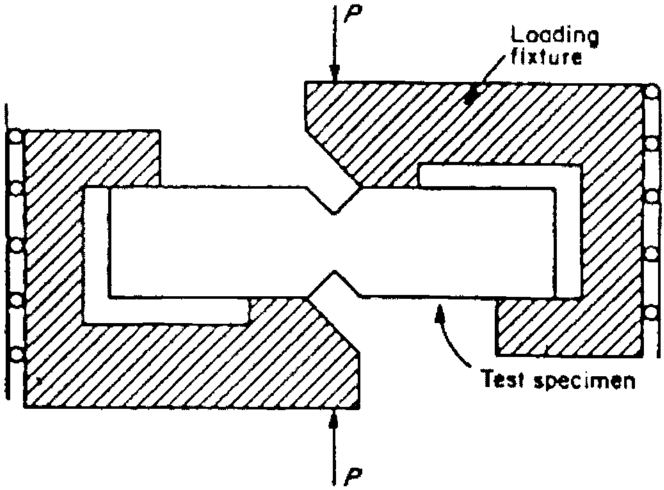



Fig. 7.9 Iosipescu shear test rig.

### 7.2.5 Fatigue

Due to the very good fatigue performance of high volume-fraction carbon fiber composite materials, there has been less emphasis on this aspect of performance than on other mechanical properties. Constant amplitude fatigue testing on undamaged coupons under axial load exhibit very flat S-N curves, indicating an insensitivity of life to cyclic load.

Fatigue performance is, however, influenced by the presence of damage and out-of-plane loading, and consequently testing is usually concentrated at the detail, sub-element, and full-scale levels, where realistic loading can be applied. As a consequence, there are no standard coupon tests recommended by testing or material authorities. Typical specimens include lap joints of both bonded and mechanically fastened configuration, stiffener run-outs, and cut-out panels. It is common to introduce damage (typically impact damage; see Chapter 12) to the expected critical areas of these specimens, and testing involves measurement of any growth of this damage.

There are increasingly moves towards developing techniques for predicting damage growth under cyclic loading using fracture mechanics approaches; however, most designs still resort to demonstration of the unlikelihood of no-flaw-growth through the service life of the aircraft.

This is not usually penalizing because the static strength reduction arising from the introduction of flaws, damage, or stress raisers means that working stresses are below the fatigue limit.

Despite the apparent resistance to fatigue, no major composite structure has been certified without a full-scale test. These tests usually include demonstration of minimum residual strength after fatigue load cycling and with the presence of damage. A typical program would be:

(1) Fatigue spectrum testing to two or more lifetimes with minor (barely visible) damage present
(2) Static ultimate load test
(3) Introduction of obviously visible damage by way of impacts and saw-cuts
(4) Fatigue cycle for a period equivalent to two or more inspection intervals
(5) Static limit load test
(6) Repair damage
(7) Fatigue for a further lifetime
(8) Residual strength test

The above would mean that all full-scale testing could be accomplished on a single structure, and although the program appears fairly conservative, it covers the fact that there is considerable scatter in fatigue life.

A point to note is that, although high volume-fraction carbon/epoxy and other carbon fiber–based laminates exhibit extremely good fatigue resistance, this is not the case for lower stiffness laminates such as glass/epoxy. These materials tend only to be used for personal aircraft and gliders for which the airworthiness requirements are less stringent.

## 7.3 Laboratory Simulation of Environmental Effects

The moisture content levels typically found in composite materials after many years of long-term service can be simulated in the laboratory using environmental chambers. Although the exact moisture profile present in components exposed to the elements cannot be easily reproduced, a good indicator of material performance can be gained by exposing the composite to a humidity level representative of the operating conditions until an equilibrium moisture content is achieved. MIL-HDBK 17 recommends that a humidity level of 85% represents a worst-case humidity level for operating under tropical conditions.

The simulation of the combination of mechanical loading and environmental conditions such as humidity and moisture can also be simulated in the laboratory through the use of servo-hydraulic testing machines and environmental generators (see Section 7.3.2).

### *7.3.1 Accelerated Moisture Conditioning*

Conditioning composite materials to a particular moisture content can be a time-consuming process. This process can be shortened if care is taken with regard to the exposure conditions. The obvious means to accelerated conditioning is to increase temperature. This is a valid approach provided that the mode of diffusion remains unchanged and that no matrix damage is introduced.

MIL-HDBK 17 recommends conditioning at a level of up to 77°C for 177°C curing composites and 68°C for 121°C curing composites. The use of boiling water to condition composites, as sometimes occurs, is unlikely to faithfully represent exposure conditions. A higher initial humidity level can be used to force moisture more rapidly into the sample center before equilibrium is achieved at the target humidity level. MIL-HDBK 17 notes that this practice is acceptable provided the humidity level does not exceed 95% relative humidity (RH). This method was published by Ciriscioli et al.[16] and describes a method for the accelerated testing of carbon/epoxy composite coupons that has been validated using mechanical testing.

### *7.3.2 Combined Loading and Environmental Conditioning*

The combination of representative loading with environmental conditioning is perhaps the best way to determine the effects of environment on composites in a short space of time in the laboratory. One such method, ENSTAFF, exists for use and includes flight types as well as ground storage conditions. The ENSTAFF[17] method of accelerated testing combines mission profiles, cyclic loads, environment, and associated temperature excursions during typical combat aircraft usage. A service condition, including loads and environment, is defined for each aircraft component, and these conditions are then applied in a reduced time frame. This allows many "flights" to be performed within a relatively short time and allows the prediction of the part performance over an extended period. The standard is designed specifically for testing of composite materials for the wing structure of combat aircraft operating under European conditions. ENSTAFF has been acknowledged by European aircraft manufacturers to cover the design criteria for composite structure in new fighter aircraft. It is applicable for tests performed at both coupon and structural level. The standard was developed jointly by West Germany, the Netherlands, and the United Kingdom.

Temperature changes due to aerodynamic heating, temperature variation with altitude, and solar radiation are all included and superimposed onto any load that may be experienced. A moisture level in the sample representing exposure to a humidity of 85% RH is maintained at all times. This is achieved by pre-conditioning the sample before testing and re-conditioning when moisture is lost. ENSTAFF is conservative in its approach in that all loads and temperature cycles are carried out at the maximum moisture content produced at the worst-case 85% RH condition. Typical service conditions will produce moisture contents below this level.

Although ENSTAFF represents a quite realistic way of accelerated testing, it must be noted that long-term degradation mechanisms (if present) may not be adequately represented by this method. This includes mechanisms such as UV exposure, erosion, or chemical reactions that may change the material properties.

## 7.4 Measurement of Residual Strength

For metallic structures, the term *residual strength* is used to define the strength of a structure after the formation of cracks, for example, by fatigue or stress corrosion. Because composite structures are brittle in nature and sensitive to the presence of even slight damage, the definition of residual strength includes its static strength when damage due to low-energy-level impacts or other flaws are present. Although high energy may lead to penetration with a little or no local delamination in a laminate, low energy may cause damage in the form of local fracture of the fibers, delamination, disbonding, or matrix cracking. These defects can occur with little visible surface damage [damage commonly known as barely visible impact damage (BVID)]. Low-energy impact damage is a concern to the composite structural designers because it may not be visible on the surface but may cause the reduction of residual strength of the structure. Numerous researchers have extensively studied the effect of impact damage on the static and fatigue strengths of composite structures. It has been demonstrated that impact damage is of more concern in compression than in tension loading, and consequently residual strength testing is usually carried out under compression loading.

Defects may arise during various stages of manufacture of materials and processing, machining, drilling, trimming, and assembly and accidental handling, or during service of the component. Some of the possible defects are summarized in Table 7.1.

Residual strength in the presence of these defects depends on various parameters such as structure, geometry, size and shape, material, damage type and its size, loading, and environmental exposure. Figure 7.10 from Ref. 18 shows the relative severity of defects such as porosity, delamination, open or filled hole, and impact damage on static strength for carbon/epoxy composite laminates. The important issue of impact damage on residual strength is discussed further in Chapters 8, 12, and 13.

Of all defects, impact damage appears to be the most critical. The laminate will typically lose up to 50% or more of its original static strength after an impact that may be barely visible to the naked eye. Consequently, most residual strength testing is carried out on coupons and structures containing impact damage, and it is assumed that this will encompass the effects of the other defects.

The following section deals with the measurement of residual strength through testing and with the reduction of the generated data.

### 7.4.1 Coupon Testing

The design of a suitable coupon test program will depend on the methods that are intended and be used in establishing values for subsequent design, often termed *design allowables*. It is sometimes assumed that flaws and service damage can be represented by holes in test coupons. A 0.25-inch (6-mm) hole in a 1.0-inch

**Table 7.1 Types and Causes of Defects in Composite Structures During Manufacture and Service**

| Cause | Process | Defect type |
|---|---|---|
| Manufacturing | Part lay-up | Fibre breakage; ply missing, ply cut, ply wrinkling or waviness, ply distortion, ply overlap, incorrect lay-up or missing plies, foreign objects inclusion, etc. |
| | Curing | Low or high local curing temperatures causing unevenly cured part or burn marks on surface, resin richness, resin starvation or dryness, porosity or voids, disbond or delamination, etc. |
| | Handling, machining, and assembly | Scratches, gouges or dents, damaged, over-size, distorted, mislocated or misoriented holes, impact damages |
| In service defects | | Impact damage by runway debris, bird strike, vehicles, hailstones, and maintenance tools<br>Lightning strike<br>Environmental damage |

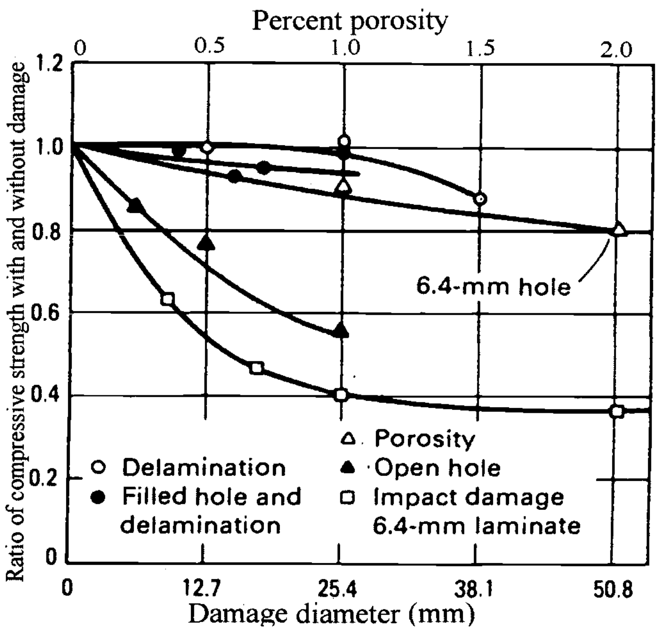



**Fig. 7.10 Effect of damage diameter on compression strength.**

(25-mm) wide specimen is often chosen as such a representative specimen. The evidence suggests that this is a reasonable assumption (Fig. 7.10) but is somewhat unconservative for the representation of certain impacts. The preferred approach is to apply an impact to a specimen of a specified energy using an impactor such as the one shown in Figure 7.11 and to obtain compression-after-impact (CAI) strength from a subsequent compression test on the impacted specimen.

The specimen configuration most widely used is given in Ref. 19. These specimens are 11.5 × 7.0 inches (292 × 178 mm) and are designed to represent a typical panel when constrained by supports on each of the four sides during the impact.

The appropriate impact energy is calculated as a function of laminate thickness from the formula:

$$\text{Impact energy} = 960\ (\pm 20)\ \text{inch lbs inch}^{-1}$$

$$(4.27 \pm 0.09\ \text{joules mm}^{-1})\ \text{laminate thickness}$$

This is assumed to be sufficient to inflict damage to the extent defined as *barely visible* (BVID) (see Chapter 12).

The specimen is trimmed after impact to 10.0 × 5.0 inches (254 × 127 mm) and mounted in a fixture such as illustrated in Figure 7.12 for compression testing. The fixture is designed to support the specimen from buckling. The side supports are a snug fit, yet they allow the specimen to slide in a vertical direction. A 0.05-inch (1.25-mm) clearance is provided between each side of the specimen to prevent any transverse load due to Poisson's deformation during the test. The upper and lower edges of the specimen are clamped between steel plates to prevent brooming. The loading rate is approximately 0.05 inches min$^{-1}$.

In some cases, the specimens are conditioned in a hot/wet environment after impact and before compression testing. The period of exposure is to last until the specimens are saturated. This is determined by repeated weighing until the weight stabilizes, indicating that no more moisture can be absorbed. For most carbon/epoxy laminates, this weight gain (i.e., moisture uptake) is around 1%. This eliminates the need to apply any subsequent "knockdown factor" (See Chapter 12) to the design allowable.

Test data are reduced as follows:

$$\text{CAI strength } \sigma_{\text{cai}} = P/bd$$

$$\text{compression modulus } E_{\text{cai}} = (P_3 - P_1)/0.002bd$$

$$\text{CAI failure strain } \varepsilon_{\text{cai}} = \sigma_{\text{cai}}/E_{\text{cai}}$$

where:

$P$ = maximum load
$P_3$ = load at 3000 microstrain
$P_1$ = load at 1000 microstrain
$b$ = average specimen width
$d$ = number of plies × nominal ply thickness

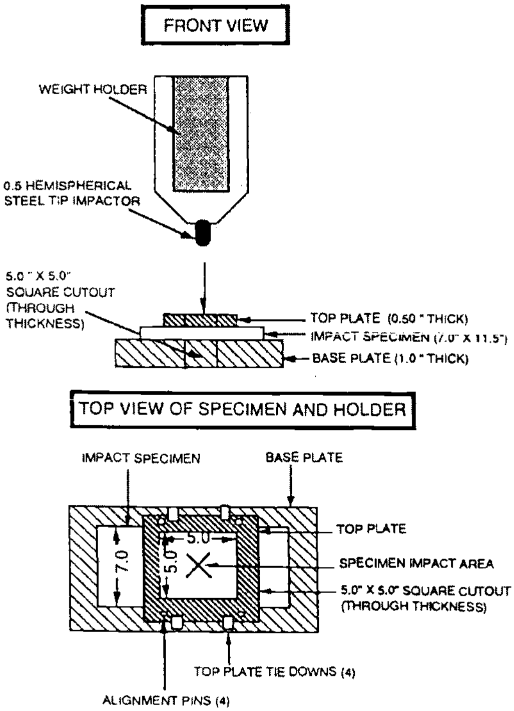



**Fig. 7.11 Specimen impactor.**

Residual strength testing may also be carried out on coupons with defects (impact damage or manufacturing flaws) that have also been subjected to fatigue loading. If the fatigue loading is such that the damage will grow, then clearly residual strength will be further reduced. To avoid this, most designs are based on a "no-flaw-growth" basis (see Chapter 12). This philosophy involves limiting design strain levels to a level that fatigue loading will not cause growth of a defect of a size that would otherwise be missed in a routine inspection. In most cases, this value is close to the limit strain (ultimate strain/1.5), and the compounding effect of fatigue loading may therefore be ignored. Figure 7.13 shows an example in which impact damage grew at cyclic strains below the nominal limit strain. In this case, the fatigue limit had to be set somewhat lower (at 60% limit static strain) to eliminate the possibility of growth in service.

### *7.4.2 Full-Scale Testing*

Final qualification or certification of the airframe will usually involve demonstration of residual strength on a full-scale structure. Generally, the structure will have gone through several equivalent lifetimes of fatigue cycling to the given loading spectrum before damage is introduced by impacting in the

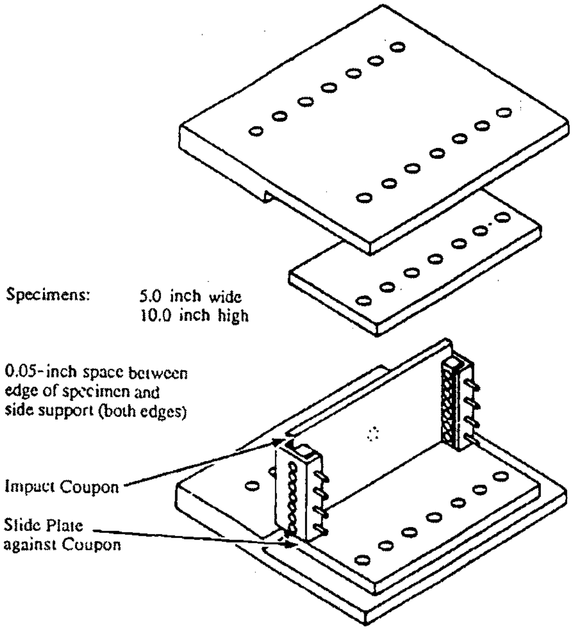



**Fig. 7.12 Compression testing fixture.**

critical locations. Fatigue loading is then continued to establish the damage growth rate. If the damage grows, the cycling must be continued from the time it is first visible until at least the next scheduled service inspection. Usually, the designers and airworthiness authorities prefer to be conservative and assume that the next inspection will miss the damage and continue for a further interval. Provided the structure has been designed to a no-flaw-growth philosophy, this will not elicit further penalty.

Mostly, full-scale tests have to be conducted at room temperature and in a nominal dry condition (actually, a significant amount of moisture is absorbed even in a laboratory environment), in which case, adjustments have to be made to the loading to account for the strength reductions at elevated temperatures. These load enhancements are effectively the reciprocal of the knockdown factors. Chapter 12 provides further explanation.

In other cases, the detrimental environmental effects are included in the test. One method used on wing structures has been to fill the wing tanks with hot water during the entire test sequence.

## 7.5 Measurement of Interlaminar Fracture Energy

Of major interest for practical application of polymer-matrix composites is their resistance to interlaminar fracture. This concern is also relevant to

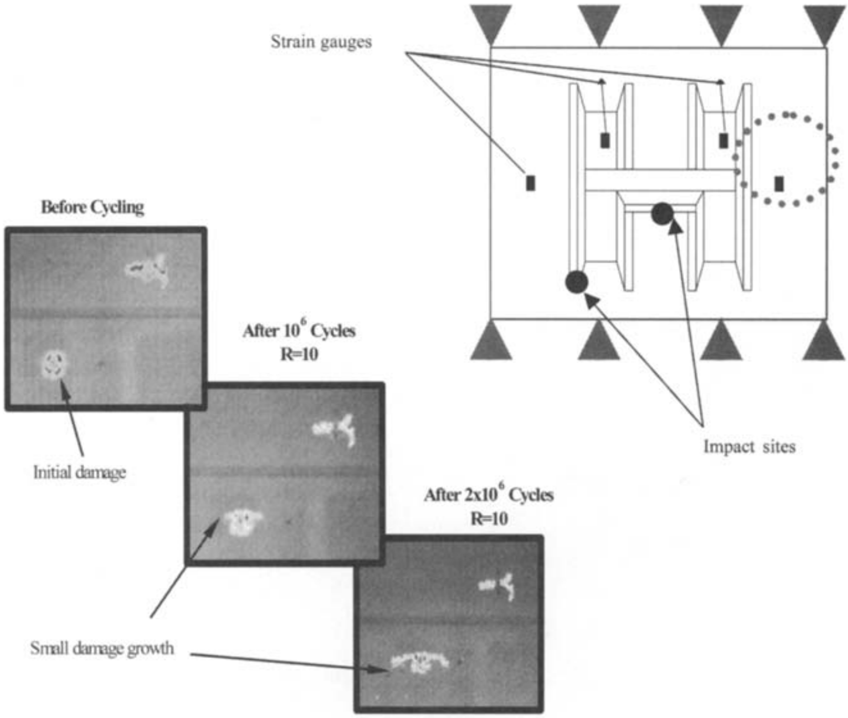



**Fig. 7.13 Fatigue loaded specimens, thermography results. Peak cycle strain 0.67 ultimate. Courtesy of the Cooperative Research Centre for Advanced Composite Structures.**

adhesively bonded composite joints, as discussed in Chapter 9. Interlaminar fracture toughness is much less of a concern with three-dimensional composites, as discussed in Chapter 14.

In addition to these microscopic failure mechanisms, at the macroscopic level, there are other discontinuities, such as delamination between plies that interact with crack growth. Delamination may develop during manufacturing due to incomplete curing or the introduction of a foreign object. Other sources of delamination are impact damage, cyclic loading, and interlaminar stresses that develop at stress-free edges or discontinuities. Delamination growth redistributes the stresses in the plies of a laminate and may influence residual stiffness, residual strength, and fatigue life.

In general, a delamination will be subjected to a crack driving force with a mixture of mode I (opening), mode II (forward shear), and mode III (anti-plane shear) stress intensities. Several test methods have been developed to evaluate the interlaminar fracture resistance of composites. In this section, a review of these methods is given.

### 7.5.1 Mode I Interlaminar Fracture Test

Double-cantilever-beam (DCB) specimens are used to measure the mode I interlaminar fracture toughness of composite laminates. There are two basic configurations of the DCB geometry: the constant width and the tapered width, as shown in Figure 7.14. In the latter geometry (because of constant strain energy release rate under a constant load), the crack length does not need to be monitored during testing. Two data-reduction methods have been applied in mode I interlaminar test compliance and fracture energy methods.

*7.5.1.1 Compliance Methods.* These methods are based on the Gurney and Hunt[20] critical strain energy release rate, $G_{IC}$, which is given by:

$$G_{IC} = \frac{P^2}{2b}\frac{dC}{da} \tag{7.1}$$

where $P$ is the critical load taken when the delamination crack propagates, $b$ the specimen width, and $a$ the crack length. Assuming a perfectly elastic and isotropic material, and taking into account the strain energy due to the bending moment compliance (C), is given by:

$$C = \frac{2a^3}{3EI} \tag{7.2}$$

where $E$ is the flexural modulus and $I$ the second moment of area. Therefore, the mode $I$ strain energy release rate in equation (7.2) for DCB specimens ($I = bh^3/12$) becomes:

$$G_{IC} = \frac{12P^2a^2}{Eb^2h^3} \tag{7.3}$$

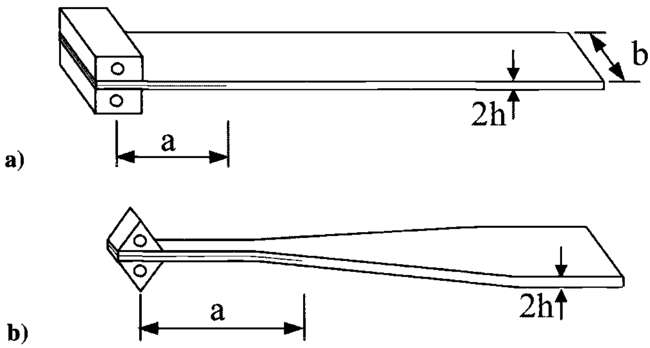



**Fig. 7.14 Mode I interlaminar fracture specimens: *a*) constant width; *b*) tapered width.**

Equation (*7.3*) also applies to the tapered-width DCB specimens where $a/b$ is constant so that $G_{IC}$ can be determined directly from the critical load $P$.

Because practical composites are mostly anisotropic/orthotropic laminates, and due to test limitations (e.g., end rotation, deflection of the crack tip) the value of the apparent elastic modulus, $E$, calculated from equation (*7.3*) varies with displacement or crack length. Therefore, by introducing some correction factors, several efforts have been made to interpret the experimental data. Some of these approaches have been simplified and used in ASTM D5528[21] standard for mode I interlaminar measuring of unidirectional composite laminates. Among these is the modified beam theory (MBT) method. In this approach:

$$G_{IC} = \frac{3P\delta}{2b(a + |\Delta|)} \tag{7.4}$$

where $\delta$ is the displacement and $\Delta$ is a correction to the crack length to take account of the imperfectly clamped beam boundary condition and defined as the intercept on the $x$-axis of a plot of the cube root of compliance versus crack length. In this approach, the modulus (E), can be determined from:

$$E = \frac{64(a + |\Delta|)^3 P}{\delta b h^3} \tag{7.5}$$

The compliance calibration (CC) method has been developed on the basis of an empirical compliance calibration, and $G_{IC}$ is given by:

$$G_{IC} = \frac{nP\delta}{2ba} \tag{7.6}$$

where the coefficient $n$ is obtained from a least squares line of a log-log plot of C versus $a$. A further modification is made to the CC method given by equation (*7.6*) and proposed by JIS (Japanese Industrial Standards); in other words, the modified compliance calibration (MCC) method:[21]

$$G_{IC} = \frac{3P^2 C^{2/3}}{2\alpha_1 bh} \tag{7.7}$$

where $\alpha$ is the slope of the least squares fit of the plot of $a/h$ versus $C^{1/3}$. It is worth noting that in Ref. 22 $G_{IC}$ values determined from three methods of data reduction—MBT, CC, and MCC methods—differed by no more than 3.1%, whereas the MBT method yielded the most conservative value of $G_{IC}$ for 80% of the specimens tested.

*7.5.1.2 Fracture Energy/Area Method.* In the fracture energy/area method, the crack extension is related to the area, $\Delta A$, enclosed between the loading and unloading paths for extension of a known crack length, $\Delta a$, as shown in Figure 7.15. The mode I strain energy release rate in this case can be defined

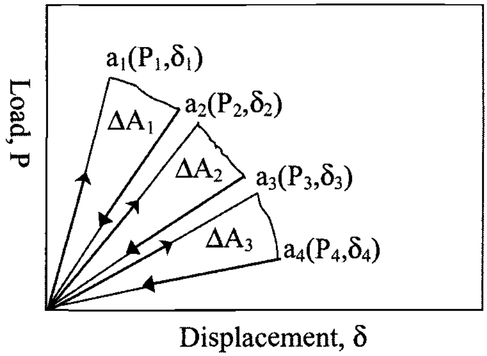



**Fig. 7.15 Loading and unloading experiments used to determine the interlaminar fracture toughness based on the area method.**

as:

$$G_{IC} = \frac{\Delta A}{b\Delta a} = \frac{1}{2b}\frac{P_1\delta_2 - P_2\delta_1}{a_2 - a_1} \tag{7.8}$$

By using equation (*7.8*), an average value of $G_{IC}$ for an extension of crack length $a_2 - a_1$ is determined by measuring the force, $P$, and the corresponding displacement, $\delta$. However, stable crack propagation is necessary for reliable application of equation (*7.8*). For this reason, interpretation of DCB test data should always be carried out in conjunction with an examination of the fracture surfaces, looking for lines of crack arrests.

*7.5.1.3 Mode II Interlaminar Fracture Test.* Both the end-notched flexure (ENF) and the end-loaded split (ELS) specimens can be used to measure pure mode II interlaminar fracture energy (Fig. 7.16).The major difficulty of the ENF specimens, which are essentially three-point flexure specimens with an embedded delamination, is in preventing any crack opening without introducing excessive friction between the crack-faces. To overcome this, it was suggested that a small piece of PTFE 0.15-0.3-mm-thick film is inserted between crack surfaces after removing the starter film.[23]

The strain energy release rate in an ENF specimen based on linear beam theory with linear elastic behavior, and by neglecting shear deformation, is given by:

$$G_{IIC} = \frac{9Pa^2\delta}{2b(2L^3 + 3a^3)} \tag{7.9}$$

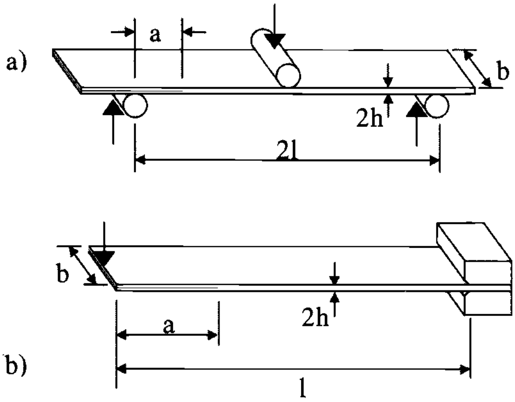



**Fig. 7.16 Mode II interlaminar fracture specimens: *a*) ENF; *b*) ELS.**

Due to unstable crack growth in this type of test specimen, the ELS configuration has been favored. For the ELS test, the corresponding expression for $G_{IIC}$ is given by:

$$G_{IIC} = \frac{9\, a^2\, P\, \delta}{2b(L^3 + 3a^3)} \tag{7.10}$$

*7.5.1.4 Mixed Mode Interlaminar Fracture Test.* Mixed mode (I and II) fracture toughness has been measured by a variety of test methods, including the cracked-lap shear (CLS) specimen, as shown in Figure 7.17. Using the CLS specimen, the force-displacement ($P$-$\delta$) curves may be obtained for various crack lengths and $dC/da$ be determined. Mixed mode fracture toughness, $G_{I-IIC}$ can then be evaluated using equation (*7.7*), or alternatively, from Ref. 24:

$$G_{I-IIC} = \frac{P^2}{2b^2}\left[\frac{1}{(Eh)_2} - \frac{1}{(Eh)_1}\right] \tag{7.11}$$

where the subscripts 1 and 2 refer to the sections indicated in Figure 7.17. Using finite element analysis, the individual components of strain energy in mode I and II can be evaluated from the CLS test results. For unidirectional specimens with the delamination placed at the mid-plane, beam theory gives a value of $G_I/G_{I-II} = 0.205$.[25]

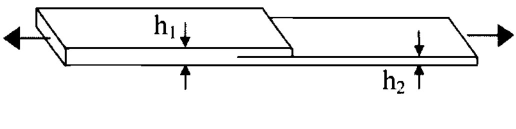



**Fig. 7.17 CLS specimen for mixed mode interlaminar fracture test.**

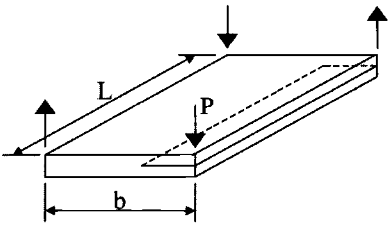



**Fig. 7.18 Mode III edge crack torsion test (ECT).**

*7.5.1.5 Mode III Interlaminar Fracture Test.* The measurement of mode III interlaminar fracture energy can be done based on the out-of-plane torsion of a cracked plate specimen,[26] as shown in Figure 7.18. A series of edge-crack torsion (ECT) specimens with different initial crack lengths are prepared. These are loaded in torsion by pushing down on one corner. The compliance can be determined from the initial parts of the load-load point displacement plots:

$$\frac{1}{C} = A\left[1 - m\left(\frac{a}{b}\right)\right] \tag{7.12}$$

Plotting $1/C$ against $a/\mathrm{b}$ gives $m$. The strain energy release rate for mode III, $G_{IIIC}$, is then obtained from the expression:

$$G_{IIIC} = \frac{mP^2C}{2Lb(1 - m(a/b))} \tag{7.13}$$

## References

[1] Adams, D. F., "Test Methods for Mechanical Properties," *Comprehensive Composite Materials*, edited by A. Kelly and C. Zweben, Elsevier, 2000.

[2] "Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials," ASTM Standard D3039/D3039M-95a.

[3] "Standard Test Method for Open-Hole Properties of Unidirectional or Crossply Fibre-resin Composites," ASTM D5766/D5766M-95.

[4] "Standard Test Method for Compressive Properties of Unidirectional or Crossply Fibre-resin Composites," ASTM Standard D3410/3410M-95

[5] "Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Material," ASTM Standard D790-84a.

[6] "Standard Guide for Testing In-Plane Shear Properties of Composite laminates," ASTM Guide D4255/D4255-83 (94).

[7] "Standard Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method," ASTM Standard D5379/D5379M-93.

[8] "Standard Test Method for In-Plane Shear Response of Polymer Matrix Composite Materials by Tensile Test of a $\pm 45°$ Laminate," ASTM Standard D3518/D3518M-94.

[9] "Standard Test Method for Apparent Interlaminar Shear Strength of Parallel Fibre Composites by Short-Beam Method," ASTM Standard D2344-84.

[10]"Compressive Properties of Oriented Fiber-Resin Composites," SACMA Recommended Test Method 1R-94.

[11]"Open Hole Compression Properties of Oriented Fiber-Resin Composites," SACMA Recommended Test Method 3R-94.

[12]Zweben, C., "Is There a Size Effect in Composites," *Composites*, Vol. 25, 199, p. 451.

[13]Chen, A. S., and Matthews, F. L., "A Review of Multiaxial/Biaxial Loading Tests for Composite Materials," *Composites*, Vol. 24, 1993, p. 395.

[14]Welsh, J. S., and Adams, D. F., "Current Status of Compression Test Methods for Composite Materials," *SAMPE Journal*, Vol. 33, 1997, p. 35.

[15]Componeschi, E. T., Jr, "Compression of Composite Materials: A Review," *Composite Materials: Fatigue and Fracture*, ASTM STP 1110, Vol. 3, p. 550.

[16]Ciriscioli, P. R., Lee, W. I., and Peterson, D. G., "Accelerated Environmental Testing of Composites," *Journal of Composite Materials*, Vol. 21, 1987, pp. 225–242.

[17]Gerharz, J. J., "Standardised Environmental Fatigue Sequence for the Evaluation of Composite Components in Combat Aircraft ENSTAFF = Environmental FalSTAFF," National Aerospace Laboratory NLR, The Netherlands, Report NLR TR 87053 U. Also published as LBF Report No. FB-179(1987), IABG Report a No. B-TF 2194 (1987), and RAE Report No. TR 87048

[18]Horton, R. E., and McCartney, J. E., "Damage Tolerance of Composites," *Composite Materials Analysis and Design*, 1984, pp. 260–267

[19]"Standard Tests for Toughened Resin Composites, Revised Edition," NASA Referenced Publication 1092—Revised 1983.

[20]Gurney, C., and Hunt, J., "Quasi-Static Crack Propagation," *Proceedings of the Royal Society of London*, Vol. A299, 1967, pp. 508–524.

[21]"Mode I Interlaminar Fracture Toughness of Unidirectional Fibre-Reinforced Polymer Matrix Composites," ASTM D5528, 1994.

[22]O'Brien, T. K., and R. H. Martin, "Round Robin Testing for Mode I Interlaminar Fracture Toughness of Composite Materials," *Journal of Composites Technology and Research*, Vol. 15, 1993, pp. 269–281.

[23]Tanaka, K., Kageyama, K. and Hojo, M., "Prestandardization Study on Mode II Interlaminar Fracture Toughness Test for CFRP in Japan," *Composites*, Vol. 26, 1995, pp. 257–267.

[24]Russel, A. J., and Street, K. N., "Moisture and Temperature Effects on the Mixed-mode Delamination Fracture of Unidirectional Carbon/Epoxy," *Delamination and Debonding of Materials*, ASTM STP 876, edited by W. S. Johnson, ASTM, Philadelphia, 1985, pp. 349–372.

[25]Brussat, T. R., Chiu, S. T., and Mostovoy, S., *Fracture Mechanics for Structural Adhesive Bonds*, AFML-TR-77-163, Air Force Materials Laboratory, Wright–Patterson AFB, Dayton, OH, 1997.

[26]Lee, S. M., "An Edge Crack Torsion Method for Mode III Delamination Fracture Testing," *Journal of Composites Technology and Research*, Vol. 15, 1993, pp. 193–201.