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Fibre-reinforced plastics — Determination of fatigue properties under cyclic loading conditions

Plastiques renforcés de fibres — Détermination des propriétés de fatigue en conditions de chargement cycliques

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Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 13003 was prepared by Technical Committee ISO/TC 61, *Plastics*, Subcommittee SC 13, *Composites and reinforcement fibres*.

Fibre-reinforced plastics — Determination of fatigue properties under cyclic loading conditions

1 Scope

This International Standard defines the general procedures for fatigue testing of fibre-reinforced plastic composites under cyclic loading conditions of constant amplitude and constant frequency. Although these general procedures are applicable to all modes of testing and test machine control, care will be required in their application in each case. Prior experience has been mainly with tensile and flexural fatigue testing based on the equivalent static (monotonic) test methods. Fatigue tests on unidirectionally reinforced carbon-fibre systems in the fibre direction are particularly difficult to perform.

In some cases, such as fracture toughness crack propagation, specific tests may exist that should be used in preference to this International Standard.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 291, *Plastics — Standard atmospheres for conditioning and testing*

ISO 527-4, *Plastics — Determination of tensile properties — Part 4: Test conditions for isotropic and orthotropic fibre-reinforced plastic composites*

ISO 527-5, *Plastics — Determination of tensile properties — Part 5: Test conditions for unidirectional fibre-reinforced plastic composites*

ISO 1268 (all parts), *Fibre-reinforced plastics — Methods of producing test plates*

ISO 14125, *Fibre-reinforced plastic composites — Determination of flexural properties*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
stress (induced in test specimen)
σ
nominal stress calculated, using the relevant equation given in the monotonic (static) test method used, from the measured load

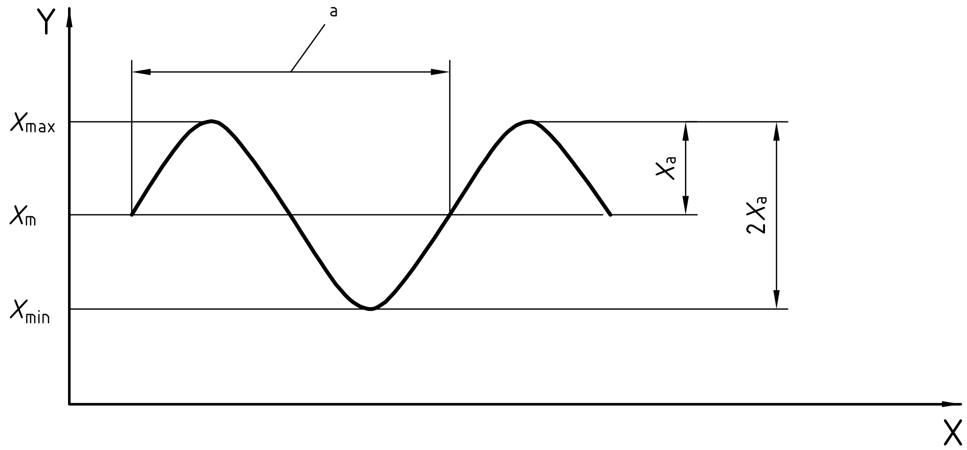
NOTE It is expressed in megapascals.

3.2
strain (imposed on test specimen)
ε
fractional elongation of the highest-loaded portion of the test specimen (e.g. the outer surface of a flexure specimen)

NOTE It is calculated from the relevant equation given in the test method used and expressed as a dimensionless ratio.

3.3
waveform
shape of the cyclic variation of the applied stress (load) or strain (displacement) between constant maximum and minimum values

NOTE The default waveform shape is a sine waveform. Figure 1 gives an example of a constant-amplitude, constant-frequency sine wave. Other waveform shapes, such as square, triangular and saw-tooth, are also used.



Key

X time

Y applied stress or strain X

X_{max} maximum (or peak) value of X

X_m mean value of X [$X_m = (X_{max} + X_{min})/2$]

X_{min} minimum (or trough) value of X

X_a amplitude of X

$2X_a$ extent of variation of X (peak-to-peak amplitude)

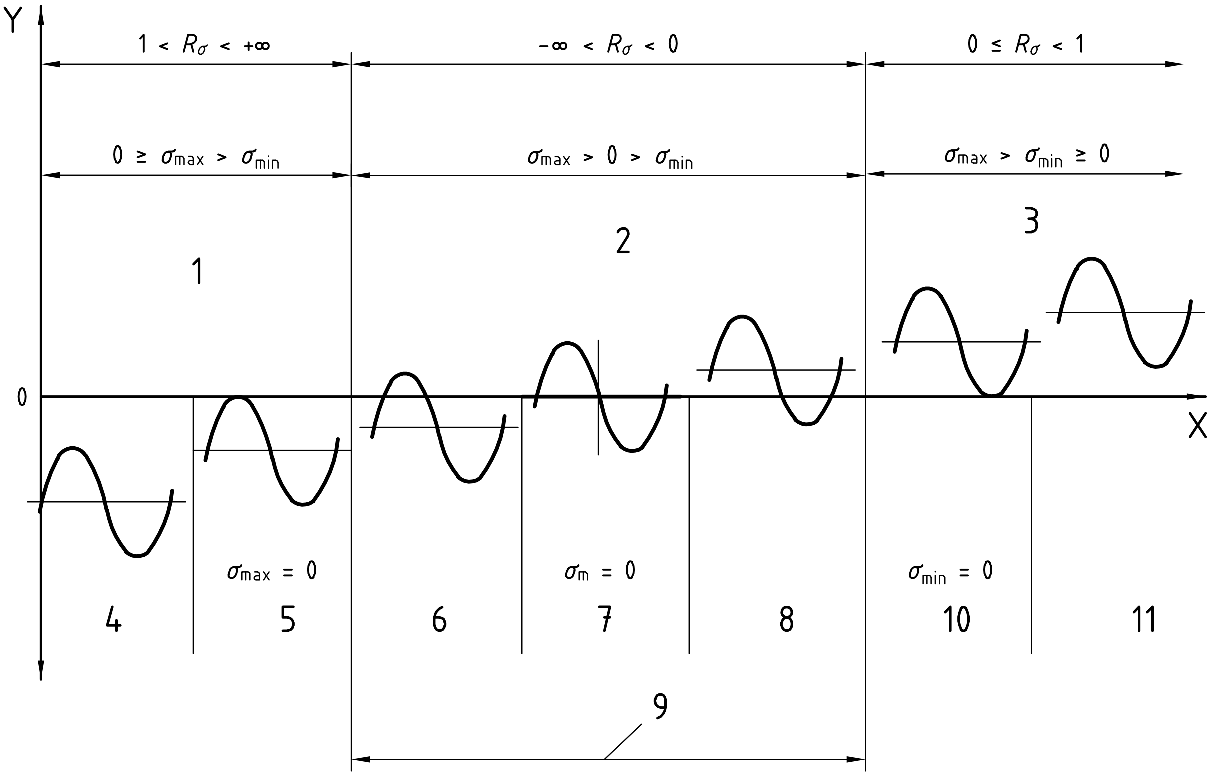
[a] 1 cycle

Figure 1 — Example of sine waveform cycle

3.4
cycle
single completed waveform from any point on the waveform (e.g. mean, peak) to the next occurrence of the same point

3.4.1
type of cycle
the type of cycle is defined by the position of the signal in relation to zero stress (load) or strain (displacement)

NOTE Figure 2 gives examples of stress cycles. For strain or deflection displacement cycles, strain or displacement terms replace stress terms.



Key

X time, t

Y stress, σ (or strain, ε)

1 compression-compression region
2 tension-compression region
3 tension-tension region
4 compression-compression cycle
5 zero-compression alternating cycle
6 compression-dominated alternating cycle
7 fully reversed or fully alternating cycle
8 tension-dominated alternating cycle
9 alternating cycles
10 zero-tension cycle
11 tension-tension cycle

Figure 2 — Examples of cycle types

3.5
frequency

f

number of cycles, or part cycles, completed in 1 s, expressed in hertz

3.6
stress, strain and displacement values

3.6.1
maximum stress
σ_{max}
maximum strain
ε_{max}
maximum displacement
d_{max}
highest value reached periodically by the stress, expressed in megapascals, or by the strain, expressed in percent, or by the displacement, expressed in millimetres

3.6.2
minimum stress
σ_{min}
minimum strain
ε_{min}
minimum displacement
d_{min}
lowest value reached by the stress, expressed in megapascals, or by the strain, expressed in percent, or by the displacement, expressed in millimetres

3.6.3
mean stress
σ_{m}
mean strain
ε_{m}
mean displacement
d_{m}
algebraic mean of the maximum and minimum stresses, strains or displacements:

$$\sigma_{m} = \frac{\sigma_{max} + \sigma_{min}}{2} \tag{1}$$

$$\varepsilon_{m} = \frac{\varepsilon_{max} + \varepsilon_{min}}{2} \tag{2}$$

$$d_{m} = \frac{d_{max} + d_{min}}{2} \tag{3}$$

3.6.4
stress amplitude
σ_{a}
strain amplitude
ε_{a}
displacement amplitude
d_{a}
value equal to half of the difference between the maximum and minimum stresses, strains or displacements:

$$\sigma_{a} = \frac{\sigma_{max} - \sigma_{min}}{2} \tag{4}$$

$$\varepsilon_{a} = \frac{\varepsilon_{max} - \varepsilon_{min}}{2} \tag{5}$$

$$d_{a} = \frac{d_{max} - d_{min}}{2} \tag{6}$$

NOTE In some cases, the extent of the stress, strain or displacement peak-to-peak variation is quoted (i.e. twice the stress, strain or displacement amplitude).

3.6.5
stress ratio
R_σ
strain ratio
R_ε
displacement ratio
R_d
ratio of the minimum stress, strain or displacement to the maximum stress, strain or displacement within a cycle:

$$R_\sigma = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} \tag{7}$$

$$R_\varepsilon = \frac{\varepsilon_{\text{min}}}{\varepsilon_{\text{max}}} \tag{8}$$

$$R_d = \frac{d_{\text{min}}}{d_{\text{max}}} \tag{9}$$

NOTE For example, R = 1 is fully reversed tension and compression of equal magnitude, while R = 0,1 is tension-tension cycling where the minimum value is 0,1 × the maximum value.

3.7
load
F
the load, measured by a load sensor, on the specimen

NOTE The maximum and minimum values for each loading cycle are F_{max} and F_{min}, expressed in newtons.

3.7.1
initial load
F_{i}
absolute value of the maximum amplitude of the load, measured before the end of the first 100 cycles or when steady conditions are obtained

NOTE Its value can be obtained either by an individual measurement or by sampling over several cycles. It is expressed in newtons.

3.7.2
load ratio
R_F
ratio of the minimum load to the maximum load within a cycle

$$R_F = \frac{F_{\text{min}}}{F_{\text{max}}}$$

3.8
initial stress
σ_{i}
stress calculated from the initial load (3.7.1)

NOTE It is expressed in megapascals.

3.9
fatigue life
N_{f}
number of cycles to which a test specimen is subjected until failure occurs or the test is terminated

NOTE 1 For displacement-controlled tests in which failure does not occur either by separation of the specimen into two or more parts or by excessive general damage (i.e. so that the load can no longer be sustained by the specimen), the end of the test is defined as a damage level (or damage rate) related to a reduction in test specimen stiffness (e.g. 5 % to 20 %). The damage level is normally taken as a 20 % reduction in the absolute value.

NOTE 2 When the test is terminated before either failure or the stiffness limit criterion is reached (i.e. the test duration to obtain failure is considered excessive), the fatigue life is not defined, but is only greater than the duration of the test. These tests are referred to as "run-outs" and the data point is often indicated on plots of stress or strain against the number of cycles by adding an arrow pointing to a higher test duration (e.g. x→, o→).

3.10
ultimate properties

3.10.1
ultimate tensile/fluxural strength at the static (standard) loading rate
UTS^S
UFS^S
parameter given by the test method used, e.g.

— UTS^S for tensile strength by ISO 527-4 or ISO 527-5;

— UFS^S for flexural strength by ISO 14125

3.10.2
ultimate tensile/fluxural strength at the fatigue loading rate
UTS^F
UFS^F
parameter given by tests at the fatigue loading rate, e.g. UTS^F for tensile strength and UFS^F for flexural strength

NOTE 1 The fatigue loading rate is taken as that resulting in failure in a time equivalent to 0,5 × the cycle time, i.e.

Test duration (s) = 0,5 × frequency (Hz)

NOTE 2 It can be set at the same frequency as the fatigue tests using a triangular waveform with an amplitude sufficient to cause ultimate failure. N.B. For a rate-dependent material, such as continuously reinforced glass-fibre-reinforced plastic, this may be significantly higher (> 40 %) than the static strength.

4 Principle

A continuously alternating mechanical load or applied displacement is applied at constant frequency to the test specimen. The test may be carried out at a constant stress (load) amplitude, a constant strain amplitude or a constant displacement amplitude.

The test method, specimen dimensions and calculations used are the same as those used in the equivalent test mode under static (monotonic) loading conditions.

NOTE 1 For example, tensile fatigue tests use ISO 527-4 or ISO 527 5 (N.B. these specimens are not suitable for fully reversed loading without support against buckling in compression, cf. ISO 14126, *Fibre-reinforced plastic composites — Determination of compressive properties in the in-plane direction*). Flexural fatigue tests use ISO 14125.

NOTE 2 There are no major differences between the operation of the fatigue machine in the different control modes (e.g. load, displacement) but there are major differences in the definition of the end-point of the test (see 3.9).

Recommendations for particular test modes are given in Annex A (flexural tests) and Annex B (tensile tests).

5 Apparatus

5.1 Test machine

A test machine suitable for the test mode selected (e.g. tension, flexure) shall be used. The equipment shall be suitable for applying the required number of cycles for several tests (e.g. $\geqslant 10^8$ cycles), in the required waveform(s) (e.g. sine, square, triangular, saw-tooth). The number of cycles applied shall be measured directly or obtained from a knowledge of the applied frequency and test duration.

5.2 Sensors and associated electronics

This equipment shall be capable of measuring continuously the variation in load, displacement or other parameters, such as strain, to within 2 % of full scale, depending on the control mode in use.

NOTE The choice of the force sensor and its full-scale range is linked to the desired measurement sensitivity and to the characteristics of the moving element of the sensor (i.e. its dimensions and mass will affect the frequency response and the magnitude of inertia effects).

The use of fatigue-rated sensors is recommended.

6 Preparation and checking of test specimens

6.1 Preparation of the test specimens

Test specimens as specified by the test method standard used shall be cut from test panels prepared in accordance with the relevant part of ISO 1268 or from flat areas of the product under test.

The mechanical properties of components or sub-components are directly linked to the structure of the material and therefore directly dependent on the processing conditions. It is recommended that testing is on test specimens which, if not taken from actual components or sub-components, are produced under conditions that are close to the actual production conditions.

6.2 Shape and dimensions

These shall be as given in the standard for the chosen test method.

6.3 Checking

Specimens shall be checked in accordance with the test method standard used. Particular care shall be taken to ensure good-quality specimens free of machining defects that could initiate premature failure.

7 Number of test specimens

For the determination of the lifetime diagram, five specimens shall be tested at a minimum of four levels of imposed stress/strain, etc., unless otherwise specified (see Note 1).

Test the five specimens monotonically to failure to measure the static (monotonic) strength for the chosen test method. Repeat tests are recommended at the fatigue loading rate for loading rate dependent materials.

NOTE 1 If it is intended to analyse the results statistically, it is advisable to increase the number of test specimens [e.g. for Weibull-type failure curves or for generating design data (e.g. 24 to 30 specimens preferred)]. To reduce the cost of preliminary or exploratory investigations, 6 specimens, and for materials research 12 specimens, may be sufficient depending on the scatter found in the test results.

NOTE 2 For loading rate sensitive materials (e.g. glass-fibre-reinforced systems), it is advisable also to measure the ultimate strength at a loading rate equivalent to the fatigue test conditions (see 3.10.2).

8 Conditioning and test environments

8.1 Conditioning

Unless otherwise specified (e.g. to investigate the effect of humidity, oil, chemical environments, other types of pretreatment), condition the test specimens as prescribed in ISO 291.

8.2 Test atmosphere

The tests shall be carried out in a standard atmosphere chosen from ISO 291 unless otherwise specified.

If other conditions are used by agreement between the parties, record full details in the test report.

NOTE In long-term testing, the state of the conditioned specimen may change unless it is maintained in the conditioning environment during the test.

9 Procedure

9.1 Measurement of dimensions of test specimens

Measure the dimensions as specified in the test method used.

9.2 Test frequency

Although normally taken as the maximum possible in order to reduce the test duration, the test frequency shall be chosen to avoid an excessive rise in the specimen temperature through autogenous (self-generated) heating. The frequency shall be measured with an accuracy of $\pm$ 2 %.

NOTE The temperature rise of the specimen surface is normally limited to 10 °C but depends on the sensitivity of the monotonic material properties to a rise in specimen temperature. The frequencies used are normally within the range from 1 Hz to 25 Hz but for loading rate dependent materials, the results can be sensitive to the frequency used (see Annexes A and B).

9.3 Conduct of the test

9.3.1 Consideration of the test conditions

Carefully review the test conditions to be used with the guidance of Annexes A and B, or review the equivalent information for other tests methods.

9.3.2 Alignment

Carefully align the specimen in the loading train in accordance with the standard for the test method used.

9.3.3 Monotonic tests

Test five specimens and determine the mean static (standard) properties in accordance with the test method standard used. For loading rate dependent materials, repeat the tests at the fatigue loading rate.

9.3.4 Fatigue tests

Select the four fatigue levels in accordance with the material under test and the maximum fatigue life of interest or, alternatively, the range of stress/strain of interest.

NOTE 1 These levels are generally evenly distributed across the range of fatigue lives, or the range of applied loads/strains, of interest. Trial tests can be used to confirm the range of test conditions to be used. Further guidance is given in Annexes A and B.

Smoothly apply the selected conditions as specified for the equipment control system used. The relationships between maximum, minimum, peak and amplitude are given in Clause 3.

NOTE 2 Users should check that the test machine control software, if relevant, uses the same relationships, particularly as far as amplitude is concerned, and adjust the machine control values, if required.

Record the applied conditions when stabilized. They may vary a little from the required conditions due to machine control limitations and specimen stiffness. Do not adjust.

Record, if available, the peak load, strain and/or displacement data. These data may be used to monitor continuously the fall in stiffness (modulus) of the specimen throughout the test.

NOTE 3 Recording the full loading hysterisis curve periodically provides important information on the changes in specimen characteristics (see Annexes A and B).

Monitor the specimen temperature for at least one specimen at each test level to ensure compliance with 9.2.

Record the number of cycles to failure, or to the loss of stiffness defined as the end-of-test criterion (see 3.9). Check that the failure mode is acceptable for the monotonic test method used, paying special attention to tab initiated or loading point initiated failures. Discard any incorrectly failing specimens and repeat these tests.

Record the mode of failure.

10 Presentation of results

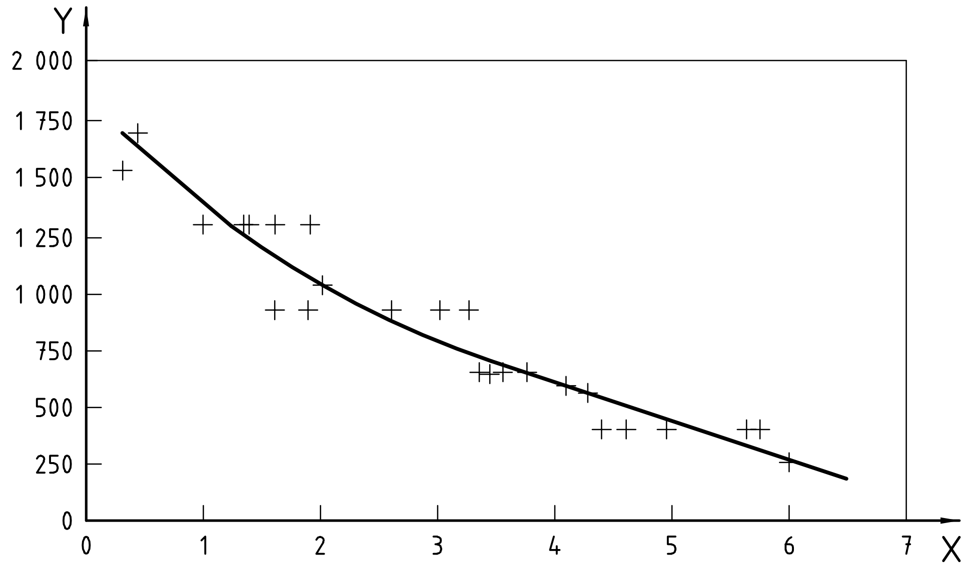
10.1 Plotting the fatigue data

The results are expressed by plotting on a graph (see Figure 3):

— on the Y-axis (linear scale): the peak stresses or strains;

— on the X-axis (log scale): the number of cycles.

This method of representation gives a plot of the Wöhler, or S-N, type. If the ultimate-strength data are plotted on the same curve, the fatigue loading rate data should be used for loading rate dependent materials. The data point is plotted at 0,5 cycles.



Key

X log N

Y stress (MPa)

Figure 3 — Example of fatigue diagram

10.2 Analysis of results

10.2.1 Curve fitting

Plot all the individual results obtained from the tests carried out, as shown in Figure 3. Fit the data using curve-fitting procedures, such as the least-square method (particularly if the data approximate to a straight line) to show the trend of the data.

In order to retain full information on the test data, it is recommended that the experimental data points be included in the test report (see Figure 3).

10.2.2 Statistical analysis of results

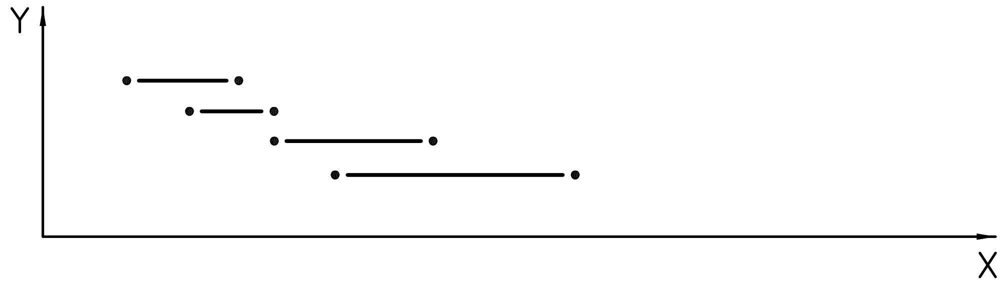
A large number of tests for each well-defined stress level and good repeatability at this stress level is required for this method of analysis.

Statistical analysis (e.g. for a Weibull-type curve) can be applied to all of the results measured at each stress level (see Figure 4). This method is imprecise in the vicinity of the limit of endurance (the curve is asymptotic) because, for identical stress levels, the lifetimes can have a large spread.

11 Precision

The precision of this test method is not known because interlaboratory data are not available.

NOTE Some information is available in bibliographic reference [3].



Key

X log N
Y stress (MPa)

Figure 4 — Statistical analysis of the results

12 Test report

The test report shall include the following information:

a) a reference to this International Standard;

b) full identification of the material tested, including:

— its designation, the nature of the matrix, the nature, type and content of the reinforcement, the type of fibre format and the stacking sequence,

— its origin, the manufacturer's reference number and the batch number,

— the manufacturing process used (if known);

c) the method of obtaining the test specimens (machining parameters);

d) the test method used and the standard applicable (tension, flexure);

e) details of the test machine, including sensor types and their accuracy;

f) the control mode (e.g. load, displacement) and waveform cycle type;

g) the test environment (temperature, humidity, etc.) and method of conditioning;

h) the total number of specimens used;

i) the mean specimen size (width × thickness × length) and shape;

j) the test geometry, e.g. the type (for instance 3-point or 4-point) and the test span(s);

k) the area or face of the test specimens subjected to stress;

l) the standard-rate ultimate static properties;

m) the fatigue-rate ultimate static properties, if required;

n) the maximum and minimum applied conditions (or mean and amplitude);

o) the R-ratio;

p) the test frequency (Hz);

q) the failure criterion used (e.g. break or loss of stiffness);

r) for each specimen:

— specimen size,

— applied stress/strain, etc., conditions,

— number of cycles to break (or cycles to 20 % loss in stiffness),

— maximum surface temperature of specimen, if above threshold value,

— failure mode;

s) typical graphs of specimen stiffness and/or damping versus number of cycles, if available;

t) plots of applied stress (or strain or displacement) versus number of cycles to failure N for all specimens [this data may be re-plotted following normalization with respect to the ultimate properties — use the fatigue-rate ultimate properties if the monotonic (static) ultimate properties are rate-dependent];

u) the date of testing.

Annex A
(informative)

Additional recommendations for flexural-test procedures

Specimen and test geometries are taken from ISO 14125. The test equipment needs modification if fully reversed loading is used but, as the specimen has a tensile-loaded face and a compression-loaded face, fully reversed tests are not normally necessary unless studying the effect of tension and compression stresses on the development of damage.

Select the specimen dimensions appropriate for the class of composite material under test from the four options in ISO 14125.

Displacement control and sine waveforms are normally used as this allows cheap equipment to be used (e.g. electric motor operated cam or lever arrangements). However, in these cases damage in the specimen leads to a loss of specimen stiffness and a fall-off in the stress developed so that a separation rupture failure is not usually obtained. This results in the need for a stiffness loss failure criterion. Load control and other shaped sine waves are possible alternative loading situations.

Test frequencies may normally be higher than for tensile tests on the same material as the autogeneous (self-generated) heating is less. The higher thermal conductivity of carbon-fibre-based systems allows higher test frequencies to be used compared with glass-fibre-based and aramid-fibre-based systems. A check should be made of the specimen temperature at each load/stress level. The acceptable level of temperature rise depends on the temperature dependence of the ultimate properties of the material under test, but a limiting value of 10 °C is recommended.

An R-ratio (minimum/maximum) of 0,1 is recommended rather than returning to the zero condition to maintain contact between the specimen and the jig. However, in displacement-controlled tests, if there is significant permanent deformation, contact with the jig may be lost at the minimum condition, so that the stiffness loss can no longer be modified.

Measure the ultimate flexural modulus, failure load and displacement at failure for:

a) a failure time of 30 s to 90 s;

b) a failure time which is appropriate to the fatigue frequency (e.g. 0,1 s for 5 Hz) (reference [1] gives more exact details and procedures).

This is to check for any rate dependence (e.g. with glass-fibre-based systems) when the data from the b) series tests are used to determine the fatigue test levels.

Typical test conditions for glass-fibre-based systems are:

— five replicates at four stress levels, e.g. 80 %, 65 %, 55 % and 40 % of the “fatigue” rate (UFS^F);

— five replicates for UFS at the “fatigue” rate (UFS^F);

— five replicates for UFS at the “standard” rate (UFS^S);

— five spares for longer (lifetime) testing, or as otherwise required.

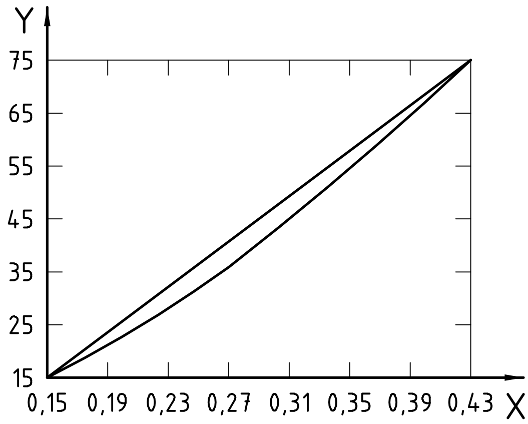
NOTE 1 For aligned carbon-fibre laminates, higher percentages will be required.

Monitor the specimen temperature for at least the first specimen at each test level. N.B. temperature rises of less than 10 °C throughout test to break can be neglected. With higher temperature rises, all tests should be monitored or the test frequency reduced. This does not apply to any rapid temperature rise associated with final failure.

If the temperature rise is not controlled, the maximum temperature should be reported for each specimen. A thermocouple attached to the specimen is usually sufficient to make the measurement.

Monitor specimen stiffness from either minimum and maximum stress (load control) and maximum and minimum strain (deflection control) or by monitoring hysteresis loops as shown in reference [2].

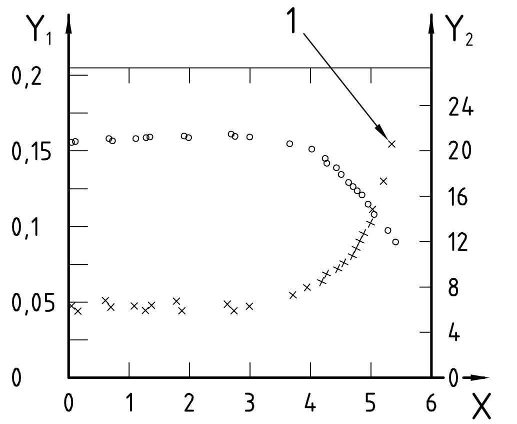
Note the stiffness as a function of test duration/number of cycles until specimen fracture or at least, normally, a 20 % or otherwise agreed loss in stiffness for displacement/strain-controlled tests is obtained.



Key

X strain, %
Y stress, MN·m^{-2}

Figure A.1 — Typical hysteresis loop
(Damping factor = 6,69 × 10^{-2}, E' = 17,45 GN·m^{-2}, number of cycles = 8 986)



Key

X number of cycles N (× 10^4)
Y_1 loss X
Y_2 modulus, GN·m^{-2}

1 failure point

Figure A.2 — Storage modulus and damping changes

Annex B
(informative)

Additional recommendations for tensile-test procedures

Specimen and test geometries are taken from ISO 527-4 and ISO 527-5. The specimen and the test equipment need modification if compression loads, including fully reversed loading, are applied as these tensile specimens are not stable under compression loads. Reference should be made to ISO 14126 for information on the requirements for avoiding buckling under compressive loads. If compressive loads are applied, consideration should also be given to reversing the loading train (e.g. wedge grips). Select the specimen dimensions from the options available for the material under test.

Load control and sine waveforms are normally used. The test end-point is normally fracture, but a stiffness loss criterion can also be used.

Test frequencies are normally lower than for flexure tests on the same materials, as the autogeneous (self-generated) heating is higher due to the larger volume of specimen under the full stress. The higher thermal conductivity of carbon-fibre-based systems allows higher test frequencies to be used compared with glass-fibre-based and aramid-fibre-based systems. A check should be made of the specimen temperature at each load/stress level. The acceptable level of temperature rise depends on the temperature dependence of the ultimate properties of the material under test, but a limiting value of 10 °C is recommended.

An R-ratio (minimum/maximum) of 0,1 is recommended rather than returning to the zero condition to avoid unloading the loading train (e.g. wedge action grips).

Measure the ultimate tensile modulus, failure stress and strain for:

a) a failure time of 30 s to 90 s;

b) a failure time which is appropriate to the fatigue frequency (e.g. 0,1 s for 5 Hz) (reference [1] gives more exact details and procedures).

This is to check for any rate dependence (e.g. with glass-fibre-based systems) when the data from the b) series tests are used to determine the fatigue test levels.

Typical test conditions for glass-fibre-based systems are:

— five replicates at four stress levels, e.g. 80 %, 55 %, 40 % and 25 % of the “fatigue” rate (UTS^F);

— five replicates for UTS at the “fatigue” rate (UTS^F);

— five replicates for UTS at the “standard” rate (UTS^S);

— five spares for longer (lifetime) testing, or as otherwise required.

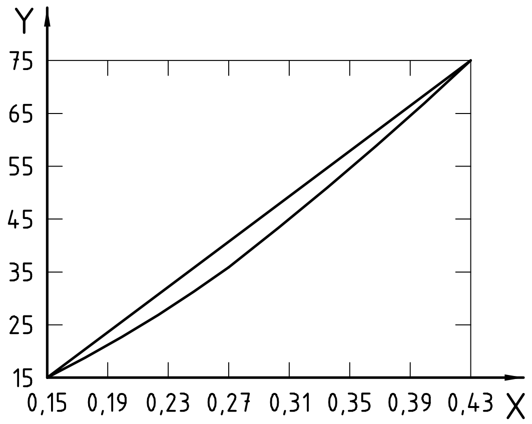
NOTE 1 For aligned carbon-fibre laminates, higher percentages will be required.

Monitor the specimen temperature for at least the first specimen at each test level. N.B. temperature rises of less than 10 °C throughout test to break can be neglected. With higher temperature rises, all tests should be monitored or the test frequency reduced. This does not apply to any rapid temperature rise associated with final failure.

If the temperature rise is not controlled, the maximum temperature should be reported for each specimen. A thermocouple attached to the specimen is usually sufficient to make the measurement.

Monitor specimen stiffness from either minimum and maximum stress (load control) and maximum and minimum strain (deflection control) or by monitoring hysteresis loops as shown in reference [2].

Note the stiffness as a function of test duration/number of cycles until specimen fracture or at least, normally, a 20 % or otherwise agreed loss in stiffness for displacement/strain-controlled tests is obtained.



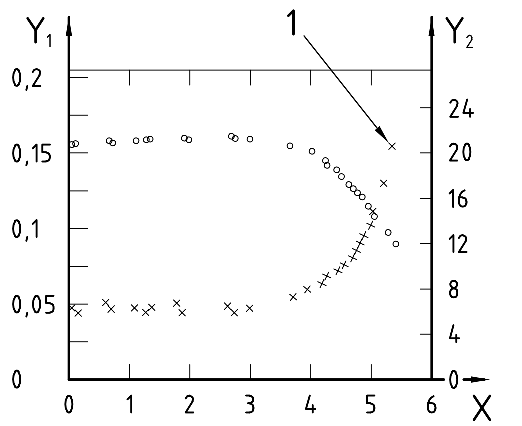
Key

X strain, %

Y stress, MN·m^{-2}

Figure B.1 — Typical hysteresis loop

(Damping factor = 6,69 × 10^{-2}, E' = 17,45 GN·m^{-2}, number of cycles = 8 986)



Key

X number of cycles N (× 10^4)

Y_1 loss X

Y_2 modulus, GN·m^{-2}

1 failure point

Figure B.2 — Storage modulus and damping changes

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