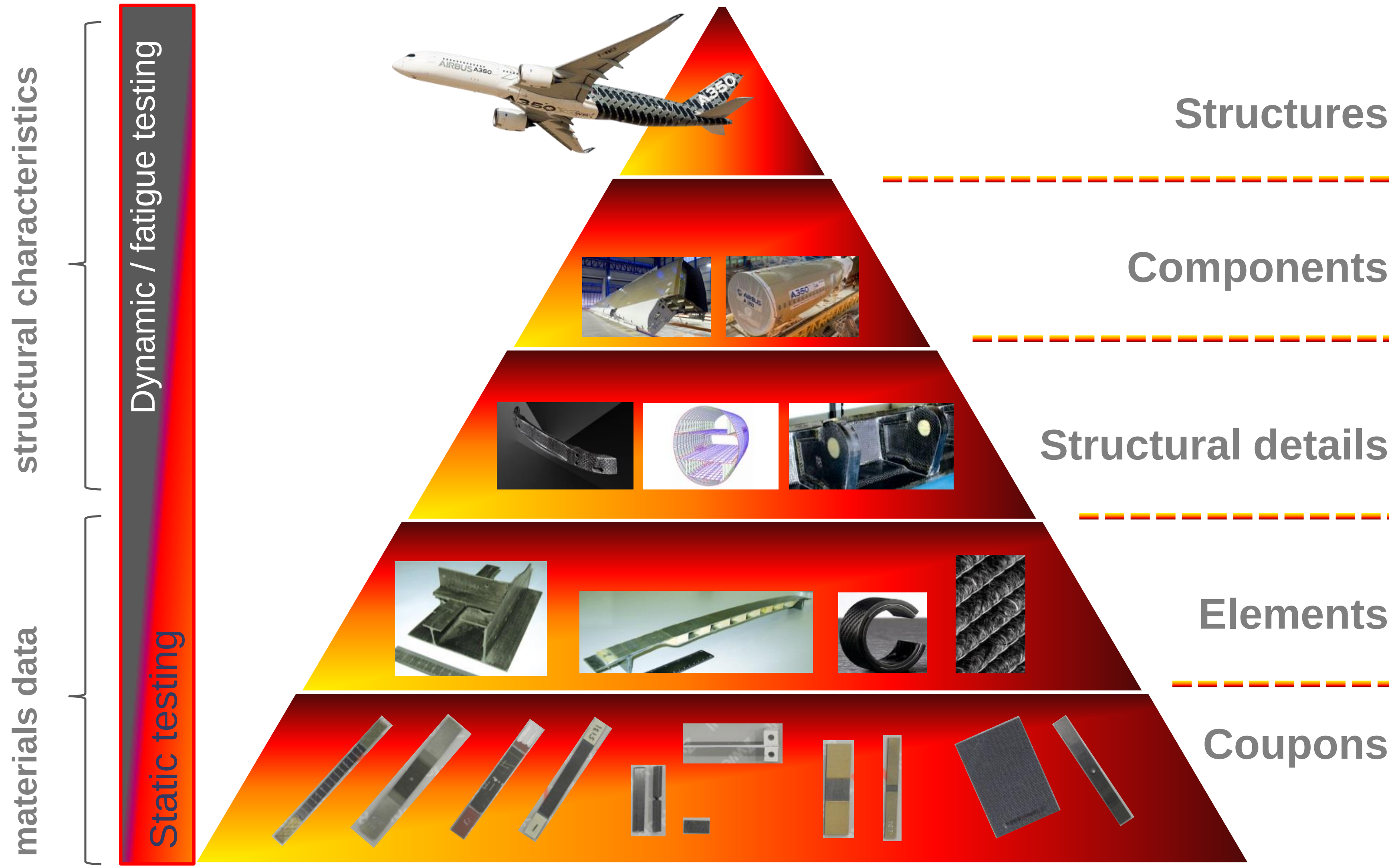
Fatigue testing of fiber-reinforced polymer matrix composites

Dr. Hannes Körber
Global Industry Manager Composites

Testing pyramid (building block approach)

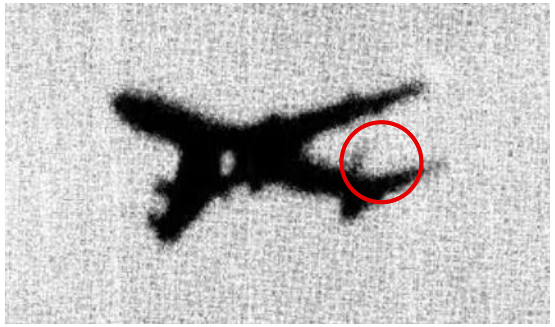


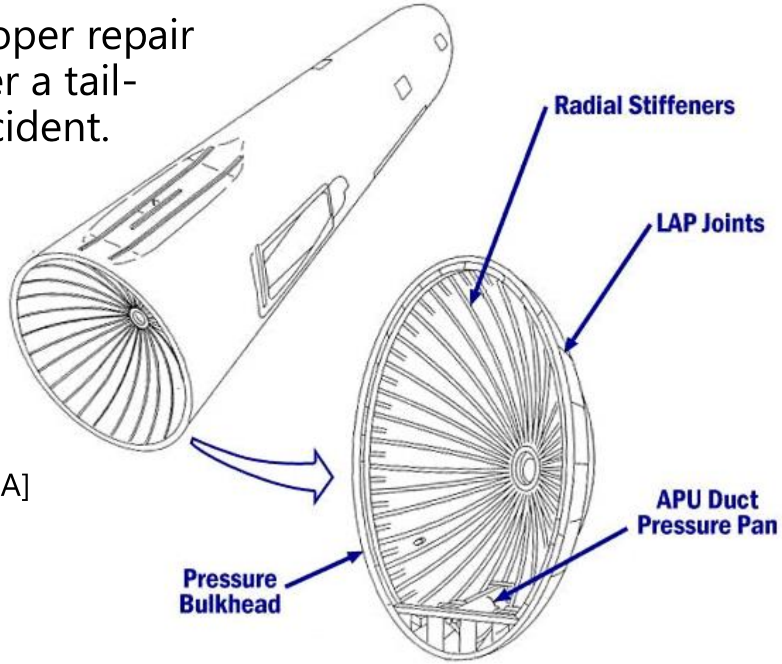
ZwickRoell

Fatigue damage caused the worst aircraft accident until today, involving a single aircraft.

- 1985 Japan Airlines Flight 123:
  - Due to a sudden failure of the rear pressure bulkhead, the aircraft lost its APU, the rudder and part of the vertical stabilizer.
  - The accident was caused by improper repair of the rear pressure bulkhead after a tail-strike 7 years prior to the fatal accident.
  - Fatigue load:

    pressurization of the cabin





[FAA]

- The good fatigue properties of CRFP composites allow a simpler pressure bulkhead design with less radial stiffeners and larger bay section.

  [IVW Kaiserslautern Annual Report 2018]

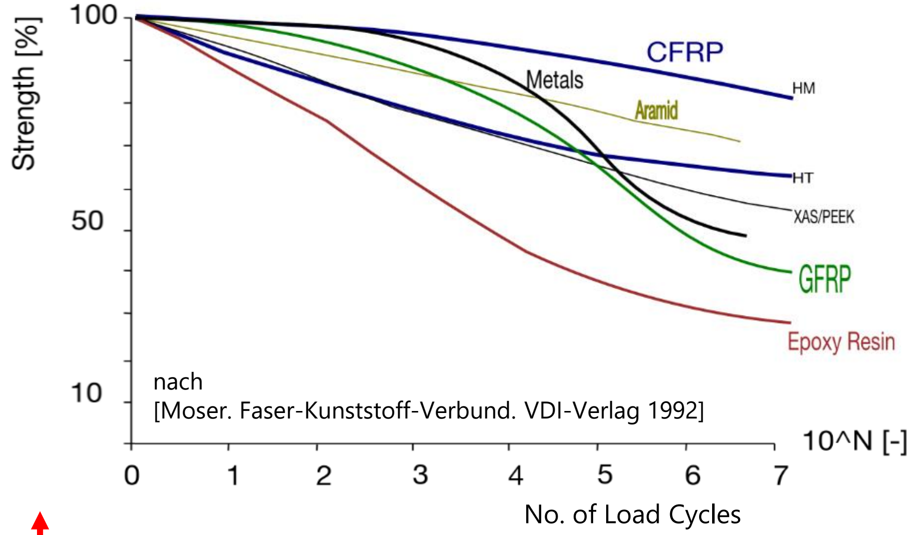
Failure due to fatigue is one of the potential causes for wind turbine blade failure.

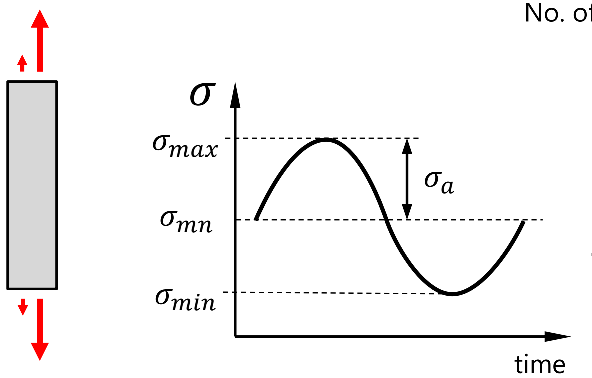
- Typical reasons for wind turbine blade failure:
  - Damage from lightning
  - Failure due to fatigue
  - Leading edge erosion
  - Damage from icing
- Causes for dynamic loading of a rotor blade:
  - Wind loads
  - Cyclic starts and stops
  - Resonance-induced structural vibrations
  - Gravity
- Fatigue loads are considered during the design and dynamic testing is carried out on all levels of the test pyramid: from coupon tests of the materials to full blade dynamic testing.

  [Katsaprakakis et al. *Energies* 14 (18), 2021]

Zwick Roell

S-N and ε-N curves describe the weakening of a material under cyclic loading. In particular CFRP composites have a more favorable fatigue response compared to metals.



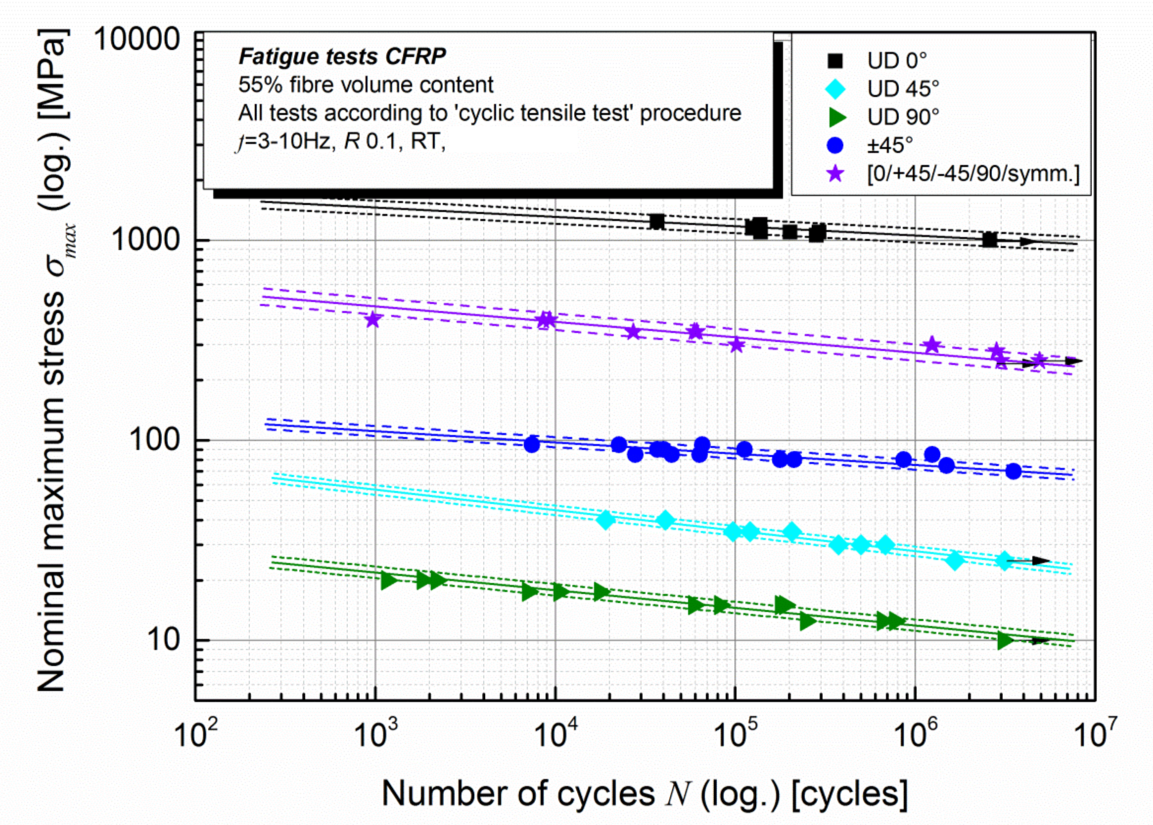


load (stress) ratio:

$$R = \frac{\sigma_{min}}{\sigma_{max}}$$

frequency:

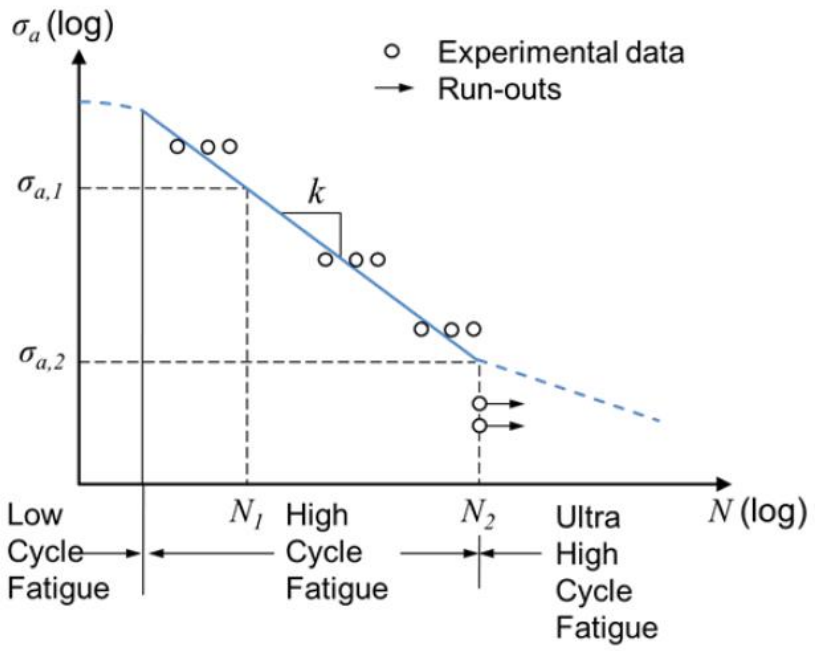
$$f$$



[PhD Brunbauer, Montanuniversität Leoben, 2015]

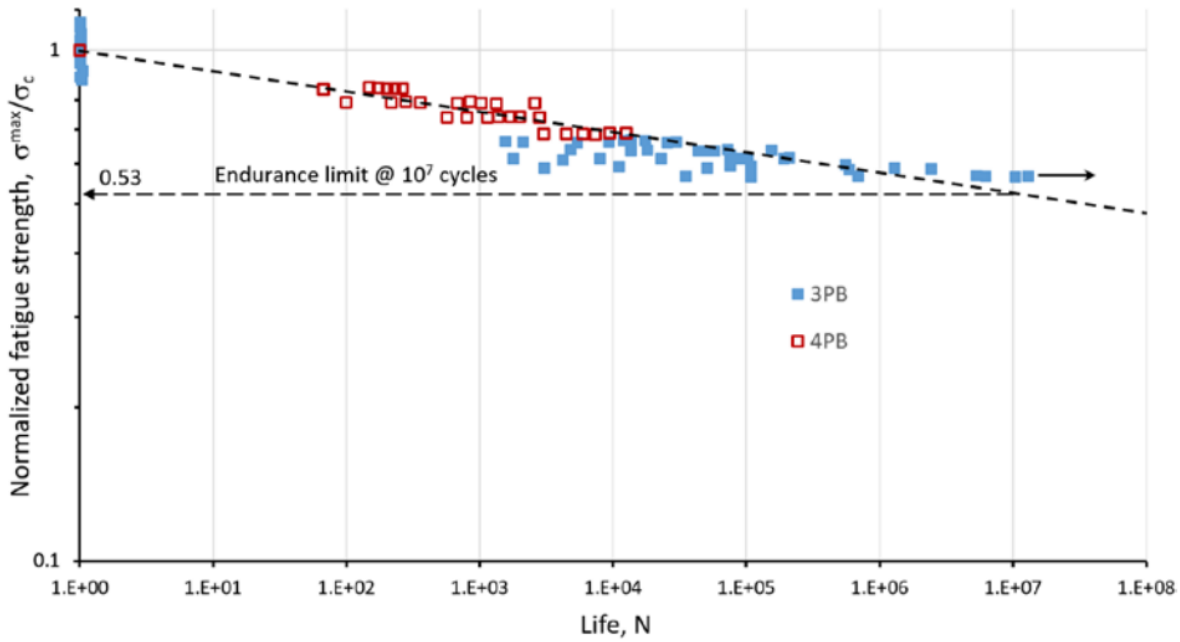
S-N curves or Wöhler lines were originally developed for metals, but have been adopted to describe the fatigue behavior or other materials, including composites.

- General illustration of an S-N curve



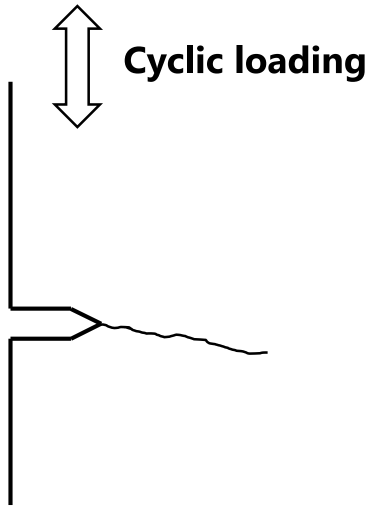
[PhD Brunbauer, Montanuniversität Leoben, 2015]

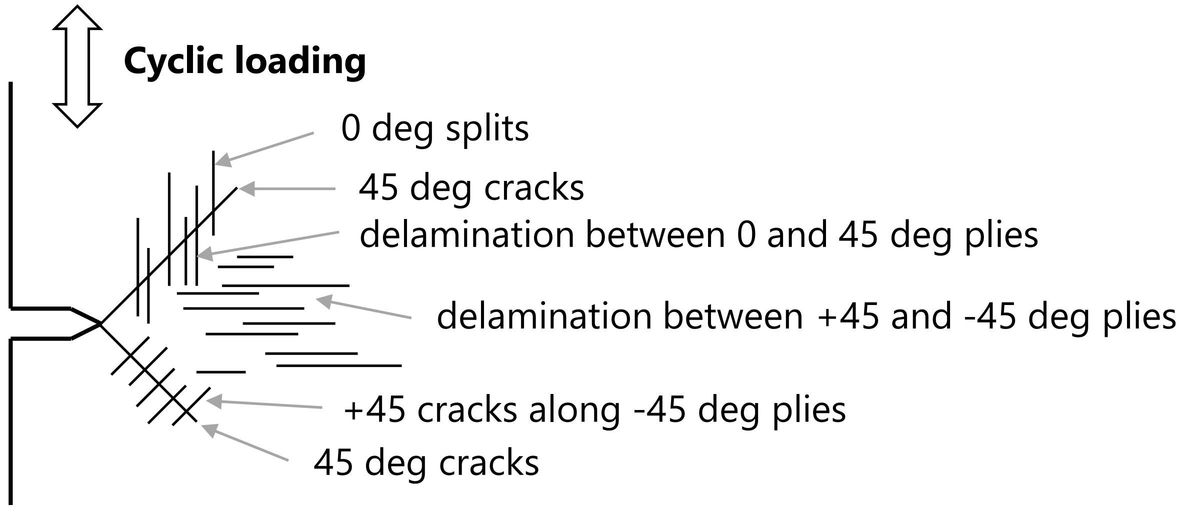
- S-N curve for matrix failure of UD carbon-epoxy composite IM7/8552 (R=0.1)



[O'Brian et al. *Int. J. Fatigue*, 2002]

In metals, a single macro-crack forms during fatigue loading. In fiber-reinforced composites, fatigue damage is dispersed with many intralaminar cracks and delaminations between plies forming prior to ultimate failure.





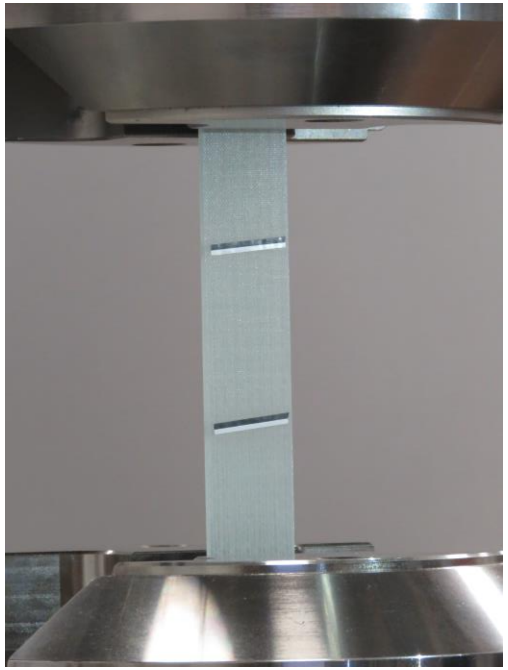
Metal: Single crack

Multidirectional composite laminate :
many cracks forming in differnent plies and in between plies

[after Curtis. The fatigue of organic matrix composites. In: *Advanced Composites*, 1989]

ZwickRoell

On the coupon level, fatigue testing of composite materials is mostly carried out as tensile and flexure tests, while other test methods are standardized as well.



GFRP tensile fatigue test as per
ISO 13003 Annex B or ASTM D3479
(markers used for optical strain measurement)

- Overview of standardized composite fatigue tests on coupon level:

Test Standard	Fatigue Test Type
ISO 13003 Annex B, ASTM D3479	Tensile
ISO 13003 Annex A, ASTM D7774 *	Flexure
ASTM D7615	Open Hole Tension (OHT) and Open Hole Compression (OHC)
ASTM D6873	Mode I Delamination Growth Onset
ASTM D6873, AITM 1-0074	Bearing Response of mechanically fastened joints
AITM 1-0075	ILSS, ILTS, OHT, OHC, FHT, FHC, Pull-Through, CAI, Lap-Shear

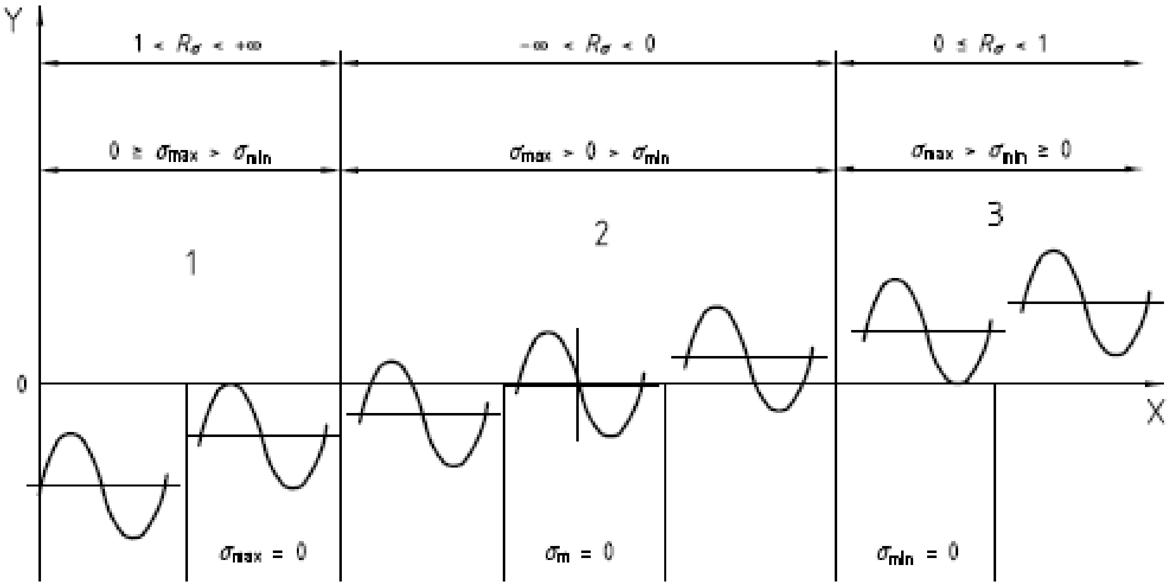
* ASTM D7774 for plastics often used as guideline for reinforced plastic composites

Fatigue test standards use specimen geometry and test fixtures of standard static tests, unless otherwise specified

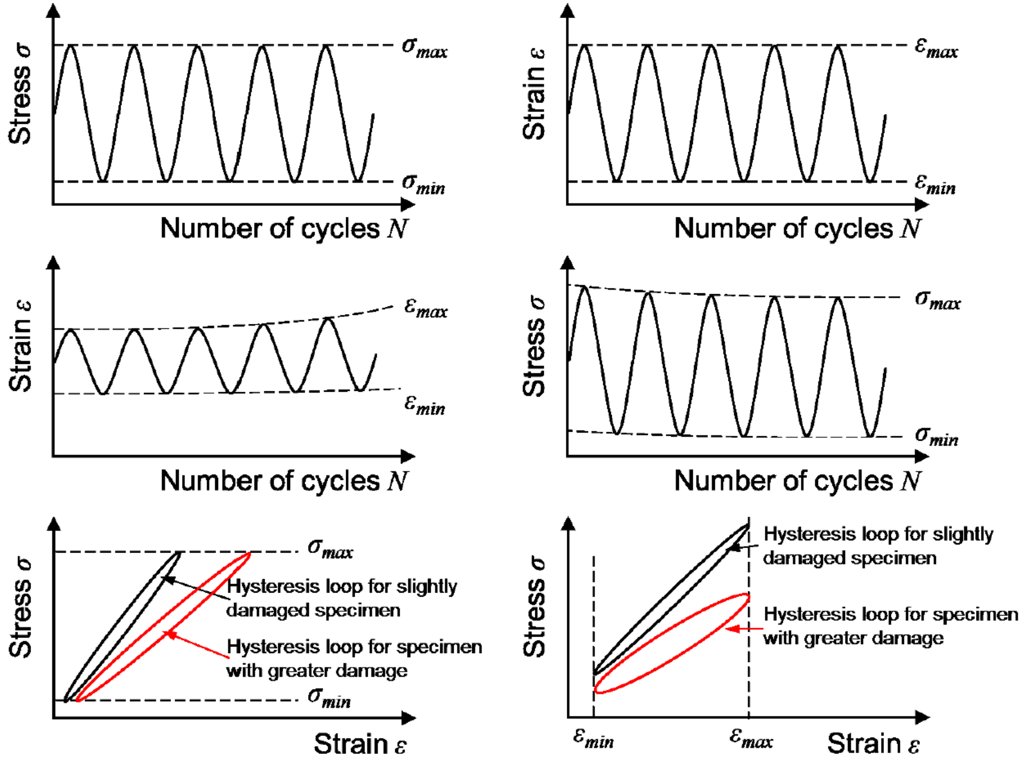
ZwickRoell

Loading and control type

Fatigue tests are either done in stress or in strain control. Load or strain ratios cover the entire range from tension to compression.



[ISO 13003]



[Stinchcomb and Bakis 1991]

ISO 13003 Annex B and ASTM D3479 contain instructions for tensile fatigue testing on the coupon level.

- Stress (force) controlled test (ISO 13003 or ASTM D3479 procedure A) or
  strain controlled test (ISO 13003 or ASTM D3479 procedure B) or displacement controlled (ISO 13003)
- Fatigue life (No. of cycles until specimen failure or test termination) defined as either:
  - Specimen rupture
  - Defined loss of dynamic stiffness
- Specimen geometry as defined in static test standards ISO 527-4,-5 or ASTM D3039

  → other non-standard specimen geometries, e.g. with tapered geometry, are used as well
- Typical load (stress) ratio: R = 0.1

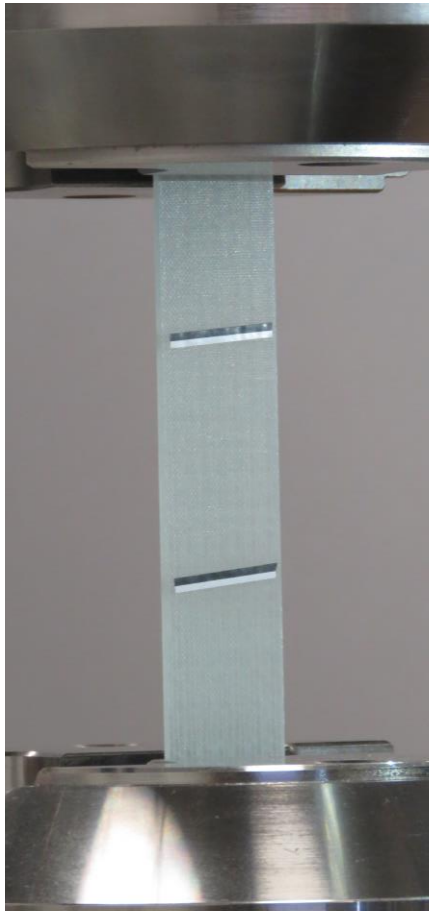
  → support fixture, adopted to specimen geometry, needed for R ratios with compression stresses or strains
- Typical test frequencies: 1 – 10 Hz
- Temperature increase of specimen during testing is to be monitored (recommendation $\Delta T \leq 10°C$)
- The <u>creation of S-N or ε-N curves</u> requires a considerable amount of specimens:

ISO 13003

No. of Tests	Purpose and Test Condition
5	Strength from static monontonic test
5	Strength at fatigue rate from monotonic test
5 x 4	5 specimens at 4 fatigue stress levels
1	Specimen for setup of PID control parameters

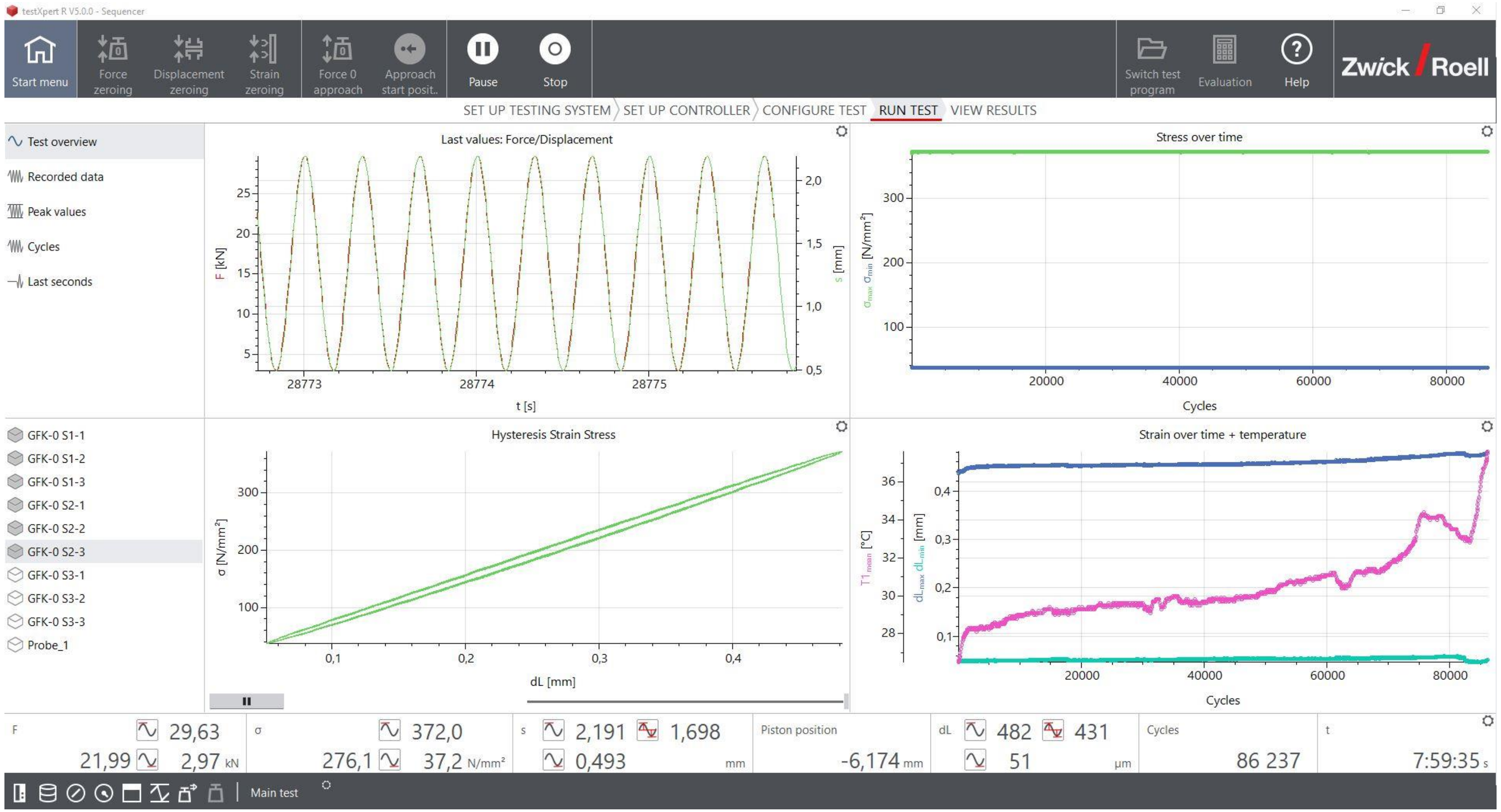
ASTM D3479

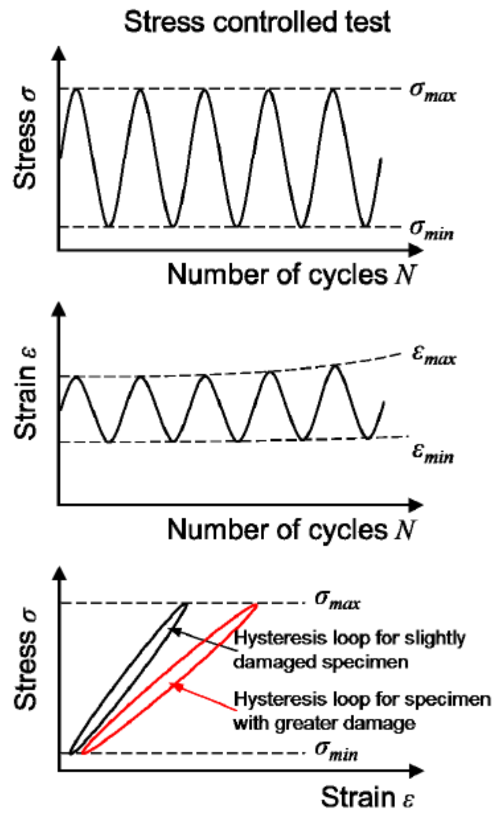
Type of Test	Minimum Number of Specimens
Preliminary and exploratory	6
Research and development testing of components and structures	12
Design allowables data	24
Reliability data	24



ZwickRoell

Simple test setup and recording of test parameters with testXpertR sequencer or predefined test programs.



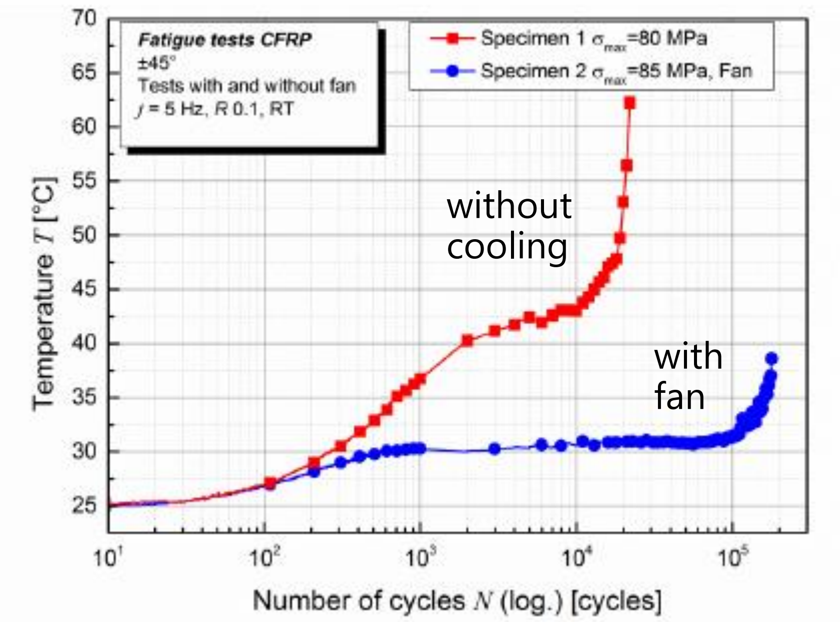


[Stinchcomb and Bakis 1991]

Internal heating of fatigue test specimens increases with increasing test frequency and must be monitored closely.

- The specimen temperature must be measured for at least one specimen per stress or strain level, directly on the specimen (e.g. by using a thermo-couple)
- The temperature curve is to be recorded
- ISO 13003 recommends that $\Delta T \leq 10°C$ (does not apply to rapid temperature increase at specimen failure)
- Test frequency shall be selected to insure that the recommended temperature bounds are met

  → typical composites test frequencies: 1 to 10 Hz
- Simple & effective: Active cooling of specimen with a fan
- More advanced: Define temperature thresholds in testing software at which the frequency is reduced and increased again
- Often a changing test frequency is not allowed in order to obtain comparable results within an S-N curve



Temperature increase in ±45° CFRP specimens under tension-tension fatigue loading due to internal heating

[Brunbauer, PhD, Montanuniversität Leoben, 2015]

ZwickRoell

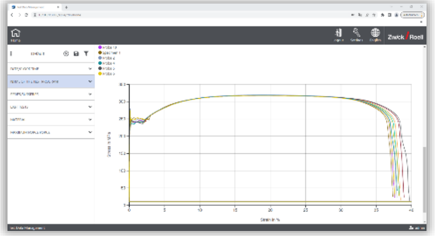
testXpert Analytics, the browser-based analysis platform for fast access to all test and machine data.

testXpert®

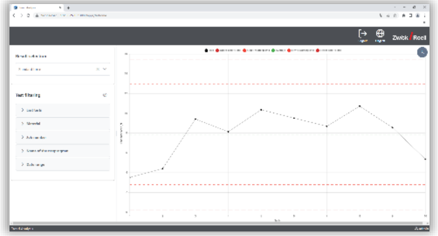
Storage

testXpert® Analytics

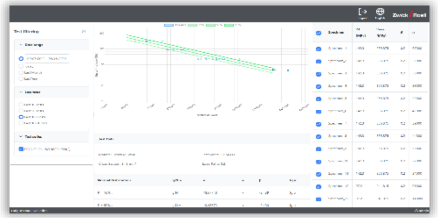
Condition Monitoring



Test Data Management



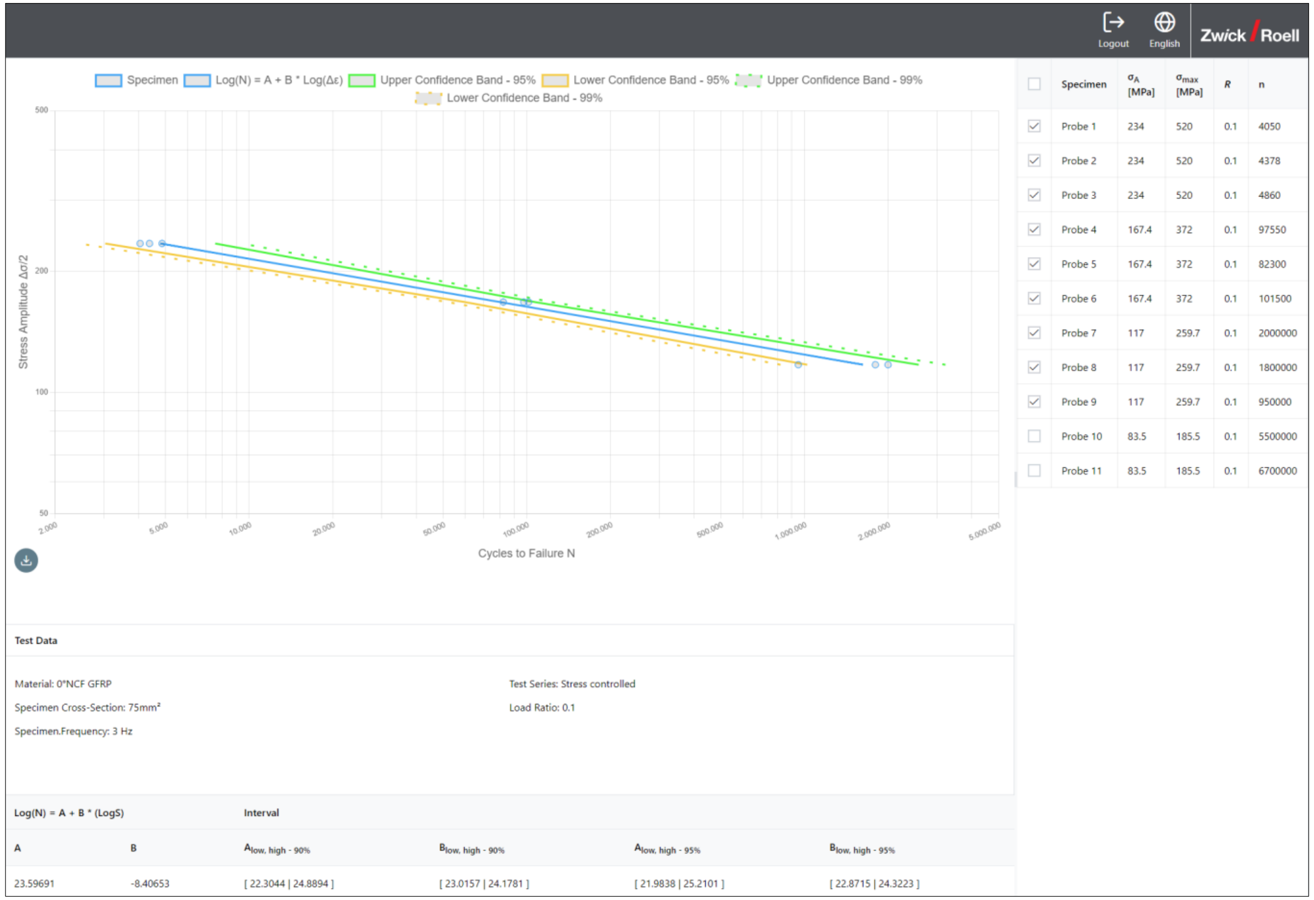
Trend Analysis



Fatigue Data Evaluation

ZwickRoell

The testXpert Analytics tool Fatigue Data Evaluation generates S-N Curves according to standard analysis procedures.



- Test data is transferred seamlessly from testXpert Research and does not need to be prepared.
- The individual specimens are visible parallel to the curve and can be selected flexibly.

- ASTM D3479 *Standard Test Method for Tension-Tension Fatigue of Polymer Matrix Composite Materials* refers to:

  ASTM E739 *Standard Practice for Statistical Analysis of Linear or Linearized Stress-Life (S-N) and Strain-Life (ε-N) Fatigue Data*

Zwick Roell

Electrodynamic testing machines for fatigue testing up to 10 kN.

- Available for load capacities from 1 to 10 kN
- Test frequency up to 100 Hz
- Electrodynamic linear drive system:
  - Low energy consumption
  - Low running costs
  - Absence of hydraulic oil
- Ideally suited for:
  - Coupon test with max. load up to 10 kN
  - Parts, components and structural details
  - Adhesives
- Can be configured with temperature chambers and a wide selection of grips, fixtures and strain measurement systems
- Available with additional torsion-drive.
- Can be used for static loading as well.

Fatigue testing machines

Servohydraulic testing machines are used for fatigue testing at higher loads.

- Our servohydraulic testing machines are available as:
  - Tabletop machines up to 25 kN
  - Floor standing machines with hydraulic cylinder mounted on the bottom (HA machines) from 50 to 250 kN
  - Floor standing machines with hydraulic cylinder mounted on the top (HB machines) from 50 to 2500 kN
- Standard frequency range up to 100 Hz
- Can be configured with temperature chambers and a wide selection of grips, fixtures and strain measurement systems
- Can be used for static loading as well.

Fatigue testing machines

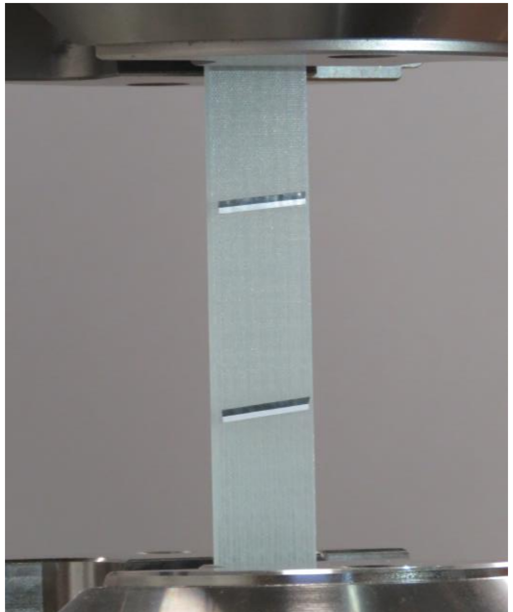
HC compact servohydraulic test machines are complete dynamic testing systems with minimal lab space requirements.

- Extra low-noise and integrated hydraulic system:
  - Serves as substructure for optional temperature chamber.
  - Eliminates additional efforts for installation of a separate hydraulic power unit.
  - Creates a very comfortable working environment.
  - Integrated cooling system of the hydraulic system prevents heating up your laboratory.
  - Simplifies transport and installation efforts.

HC100 Compact: The all-in-one servohydraulic testing machine with integrated hydraulic power pack for static and fatigue testing of composites.

Testing in a wide temperature range
from -70°C to +250°C
(depending on test typ and test fixture)

Dynamic (ISO13003, ASTM D3479)

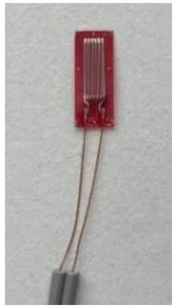


Markers for non-contact strain measurement (**videoXtens dynamic)**

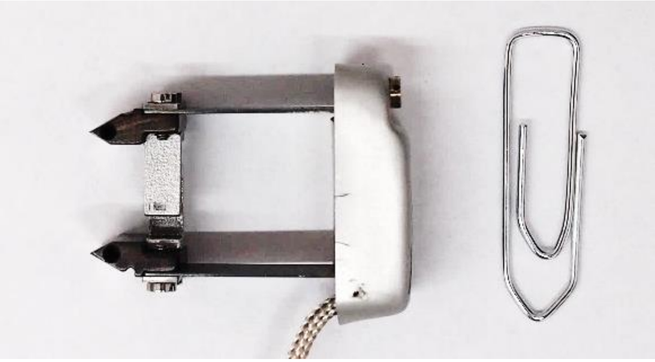
Static

Often tensile fatigue tests are done stress controlled until ultimate specimen failure. For additional strain measurement or strain controlled tests, different options are available.

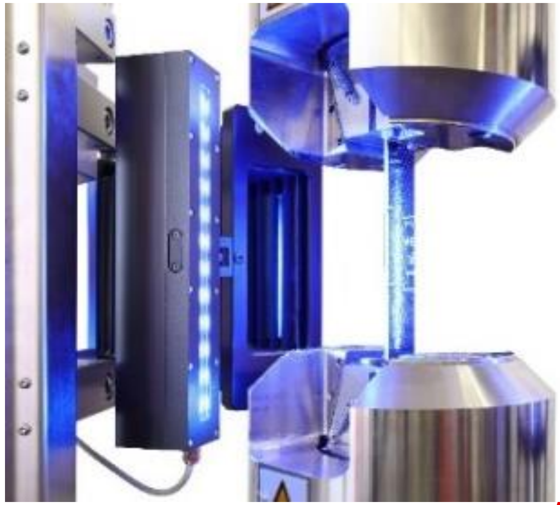
- **Strain Gauges**
  - Established and versatile
  - Application expertise needed
  - One-time use item
  - Very local measurement
  - Welding points are fatigue loaded as well and may fail prior to test end



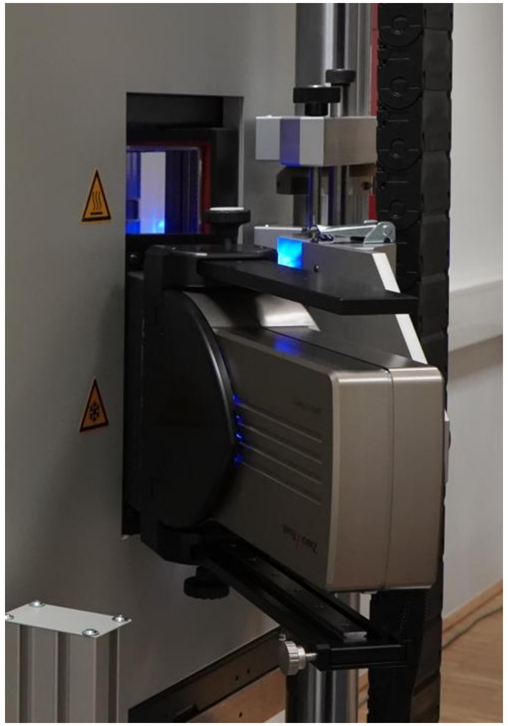
- **Clip-on Extensometer**
  - Well-known and established
  - Light models available for dynamic testing
  - Should be removed prior to specimen failure to avoid damage of extensometer
  - May loose contact due to surface damage and delamination of the composite specimen



- **Video Extensometer**
  - Strain measurement until ultimate failure possible
  - Non contact measurement does not effect sensitive specimens
  - No signal loss as long as adhesive markers stay on.



The videoXtens dynamic is a truly versatile optical strain measurement system for dynamic composites testing.



- Convenient additional strain measurement for stress-controlled fatigue tests
- From small to large strain measurement for strain-controlled fatigue tests up to 30Hz
- Axial and transverse strain measurement (adhesive markers and specimen edge)
- Ambient and non-ambient temperature testing

- 90mm Field of View (FOV)
- Measuring speed: 300 to 4000 fps at room temperature
max 1000 fps with temperature chamber
- Resolution [µm]: ±0.15 at 300 fps and room temperature
± 0.2 + 0.02/10°C at 300 fps and T-chamber
- Calibration (<2000 fps): ISO 9513 – Class 0.5, ASTM E83 – Class B1
- Analog stand-alone system for use with non-ZR machines

Fatigue data is requested by the automobile industry. But no detailed method is available.

Background

- The automotive industry requests S/N curves for simulations purposes, especially for fiber filled engineering plastics such as PA66 or POM.
- ASTM D7791 defines fatigue in tension and compression is a quite general way, which is not sufficient to provide well reproducible results.
- A CAMPUS workgroup including stakeholders from Materials Producers, Automotive Industry and Equipment Manufacturers was formed to develop and approve a method. These works are still ongoing.
- A preliminary work item was proposed in 9/2023 to ISO TC61/SC2

Objectives

- Define a fatigue method for polymers giving reproducible test results
  - Define requirements for the test equipment
  - Define test specimen and conditioning
  - Address the problem of alignment
  - Address the problem of self heating
  - Define test sequences offering an optimum between reproducibility of the results and needed test time

Preliminary work item

Zwick / Roell

zwickroell.com