Chapter 6

Mechanical Testing of Composite and Advanced Materials

Tran Huu Nam and Bohdana Marvalová

Department of Applied Mechanics – TU Liberec

Contents

Mechanical property characterization

- In this modern age, while designing a structure, a special care is always taken, that the structure under design should be able to withstand the stresses under the various load conditions without failure.
- The characterization of mechanical properties of composite materials is very important from design and analysis as well as life prediction point of view.
- Mechanical properties of materials:
  - Strength
  - Elasticity
  - Toughness
  - Ductility
  - Brittleness
  - Hardness
  - Etc…

Stress and strain of a body

- **Stress:** the resistance of unit area to deformation; i.e.

$$\sigma = \frac{P}{A}$$

where, σ = stress, P = load or force acting on body, and A = the cross-sectional area of the body.

- **Strain:** the deformation per unit length; i.e.

$$\varepsilon = \frac{\delta L}{L_o} \qquad \text{Or in percentage form} \qquad \varepsilon = \frac{\delta L}{L_o} \times 100 \ \%$$

where, ε = strain, δL = change of length of the body, and L_o = the original length of the body. The percentage form is usually called the **percentage elongation**. There is a term called **percentage reduction in area**:

$$\text{Percentage reduction in area} = \frac{\delta A}{A_o} \times 100 \ \%$$

where, δA = change of cross-sectional area of the body, and A_o = the original cross-sectional area of the body.

6.1. Introduction

Strain measurement

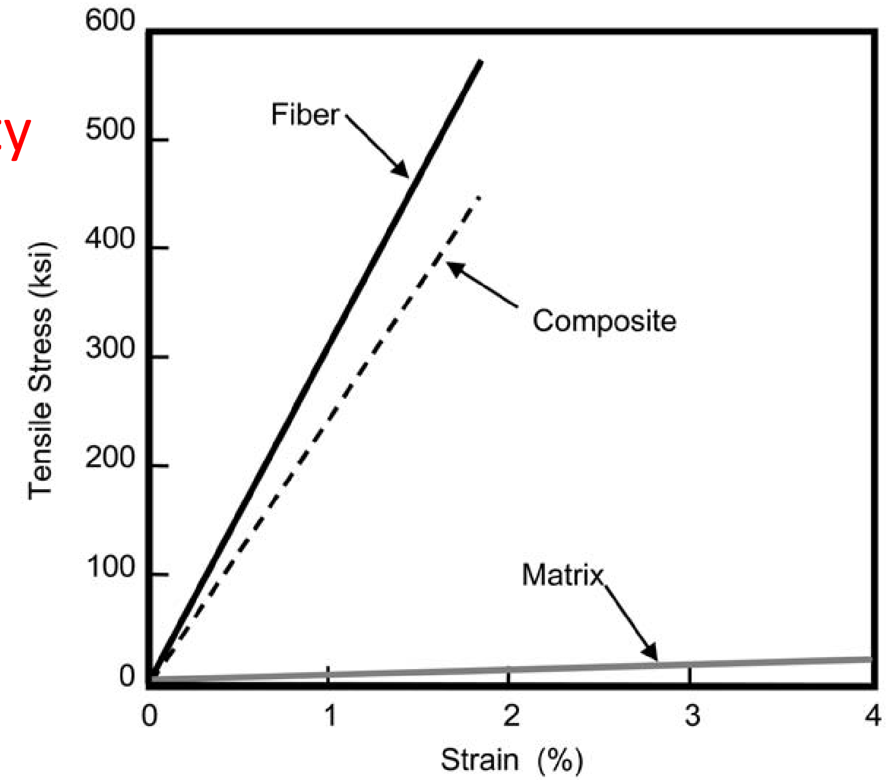
There are three commonly used methods to measure the strains. The strains can be measured using contacting (extensometers, strain gages), and non-contacting (optical) methods (video extensometry, laser extensometer, and digital image correlation (DIC) techniques).

1. Extensometers: They provide average strain over a finite length, typically of the order 1 in (25.4 mm). These are used primarily for measurement of axial strains. They can also be used to measure transverse strains.
2. Strain gages: The strain gages can be uniaxial, bi-directional and rosettes. They measure strain in one, two and three directions, respectively.
3. Video extensometry, laser extensometer, and DIC: They are optical methods that compare images of a tested specimen's surface to yield complete field strain and displacement maps.

6.1. Introduction

Mechanical testing of composites and their constituents

- Mechanical tests done to determine intrinsic material properties such as strength, strain, and modulus for use in design and analysis (major emphasis here).
- Mechanical tests done to determine quality or acceptability of specific components during manufacturing.
- Test methods
    - Tensile
    - Compression
    - Bending
    - Shear
    - Others



Partial List of Standardization Groups

USA

American Society for Testing and Materials (ASTM)
MIL-HDBK-17 Committee (http://www.mil17.org/)
Suppliers of Advanced Composite Materials Association (SACMA)

Europe

Deutsches Institut Fur Normung (DIN)
Association Francaise de Normalization (AFNOR)
British Standards Institute (BSI)

East Asia

Japanese Industrial Standards (JIS)

International

International Organization for Standardization (ISO)

6.1. Introduction

ASTM Standard Test Methods*

Lamina/Laminate Mechanical Tests

D3039/D3039M-17: Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials

D3552-17: Standard Test Method for Tensile Properties of Fiber Reinforced Metal Matrix Composites

D3518 / D3518M – 18: Standard Test Method for In-Plane Shear Response of Polymer Matrix Composite Materials by Tensile Test of a ±45° Laminate

D2344/D2344M-16: Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates

…

Constituent/Precursor Properties

D3529 – 16: Standard Test Methods for Constituent Content of Composite Prepreg

D3379--Test Method for Tensile Strength and Young's Modulus for High Modulus Single-Filament Materials

D4018 – 17: Standard Test Methods for Properties of Continuous Filament Carbon and Graphite Fiber Tows

…

* Found in Vol. 15.03 of ASTM Annual Book of Standards

Mechanical testing of the fiber

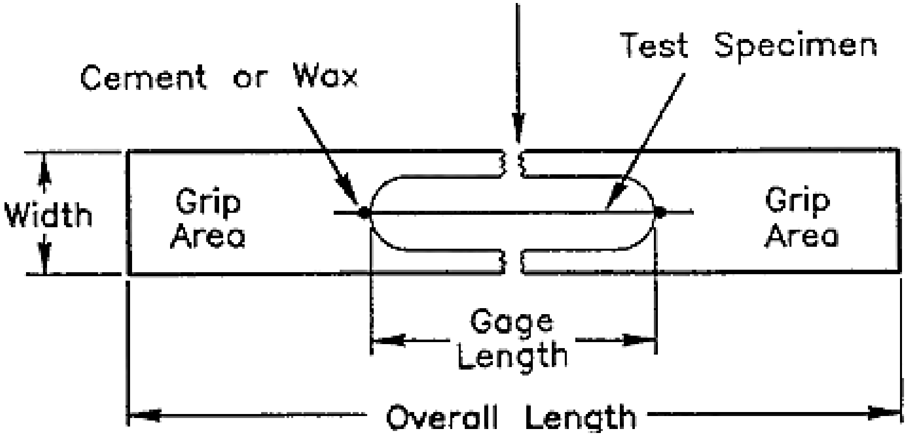
Direct measurement of fiber longitudinal properties E_{f1} and $S_{f1}(+)$

- Single fiber tensile test

$$T_f = \frac{F}{A}$$

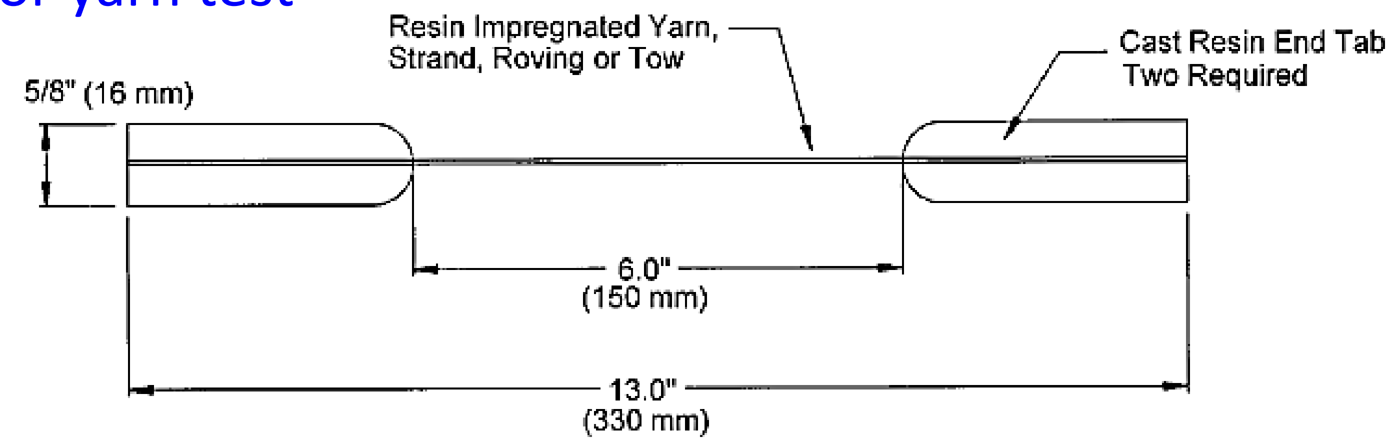
ASTM D 3379

T_f Tensile strength of fiber (N/mm^2)
F Failure load (N)
A Average fiber area of cross section (mm^2)



- Fiber tow or yarn test

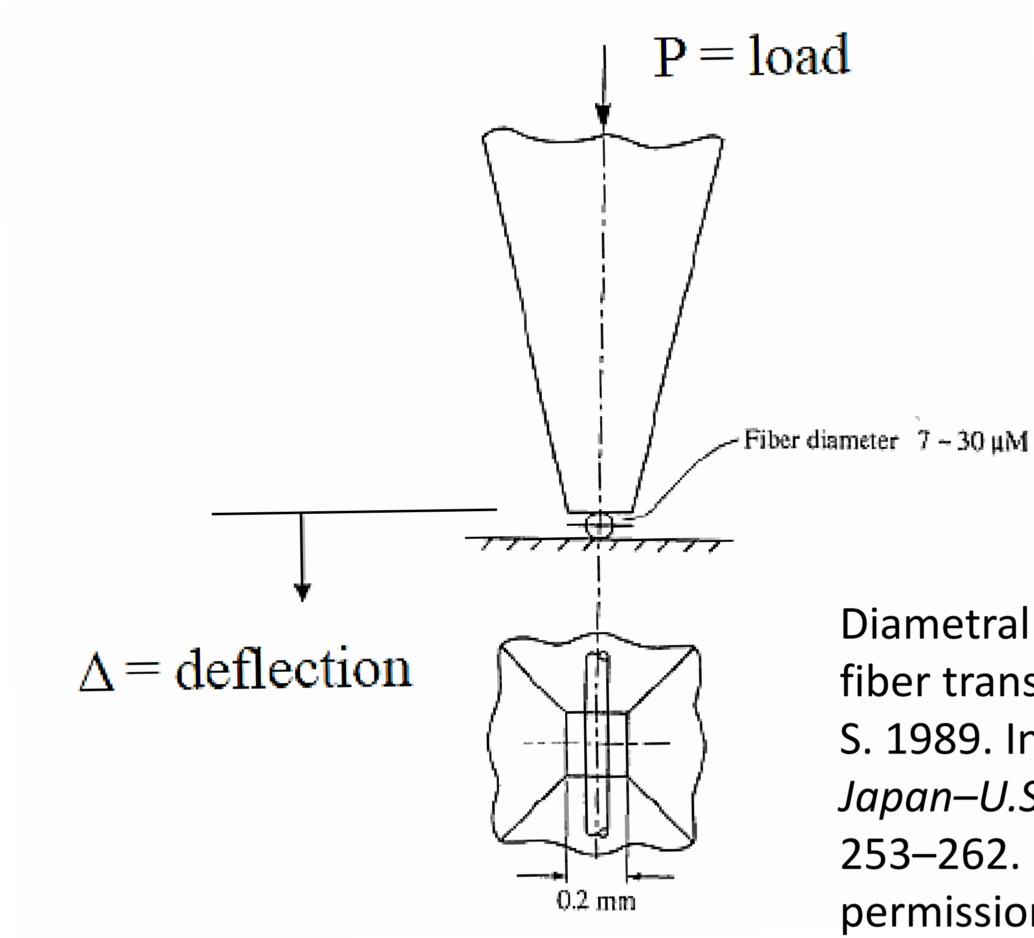
ASTM D 4018

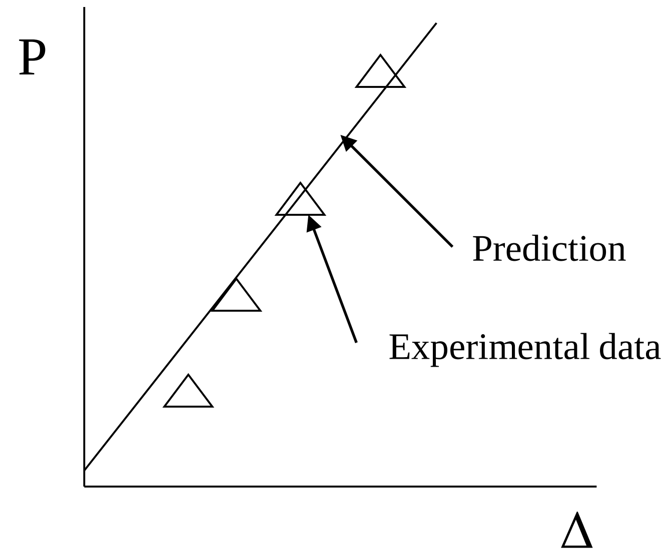


6.2. Mechanical testing of fiber and matrix

Mechanical testing of the fiber

Indirect measurement of fiber transverse modulus E_{f2}

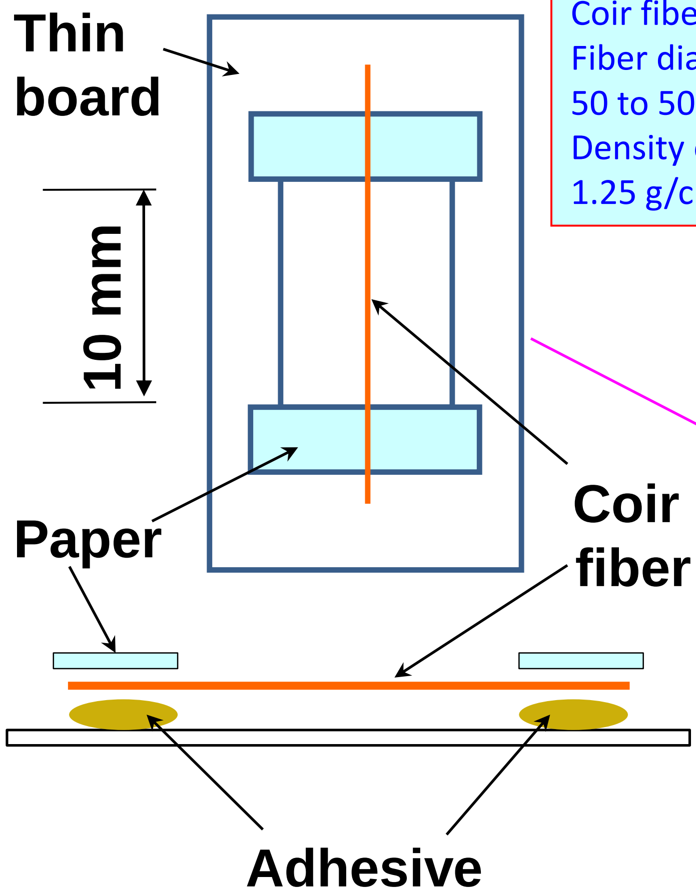




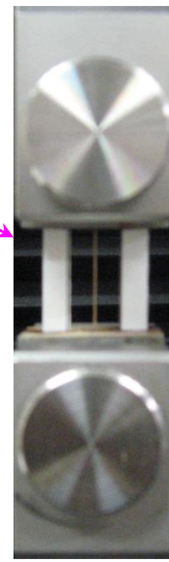
Diametral compression of fiber for measurement of fiber transverse Young's modulus. (From Kawabata, S. 1989. In Vinson, J.R. ed., *Proceedings of the 4th Japan–U.S. Conference on Composite Materials*, pp. 253–262. CRC Press, Boca Raton, FL. With permission.)

6.2. Mechanical testing of fiber and matrix

Single fiber tensile specimen



Coir fiber: Betrimex JSC., VN.
Fiber diameter varies from 50 to 500 μm.
Density of coir fiber is about 1.25 g/cm^3



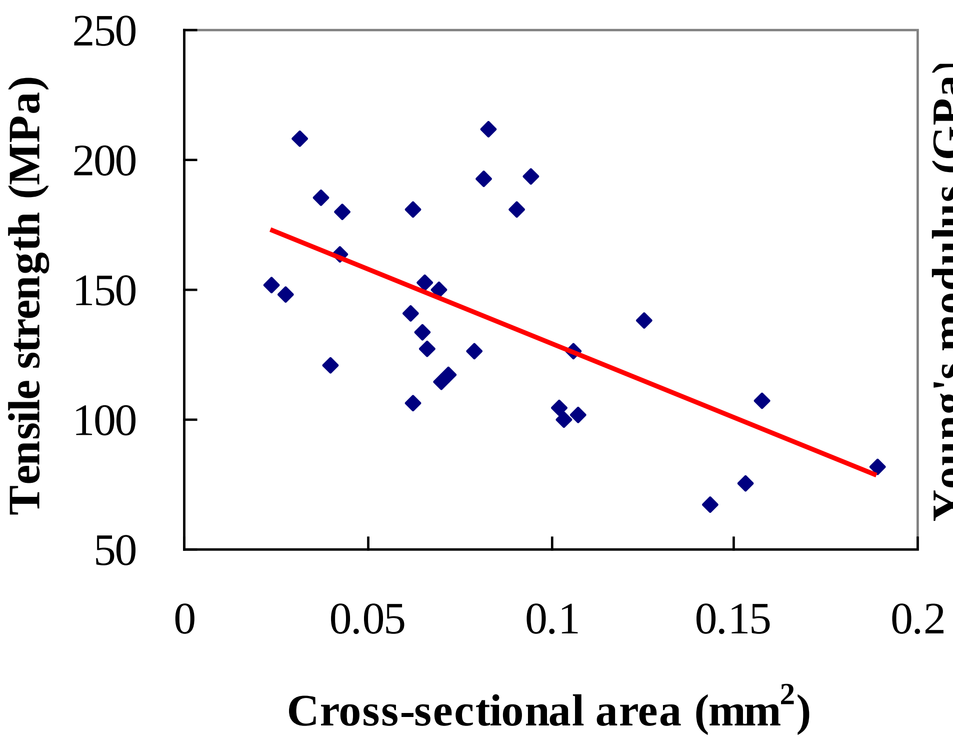
Universal testing machine INSTRON 4442

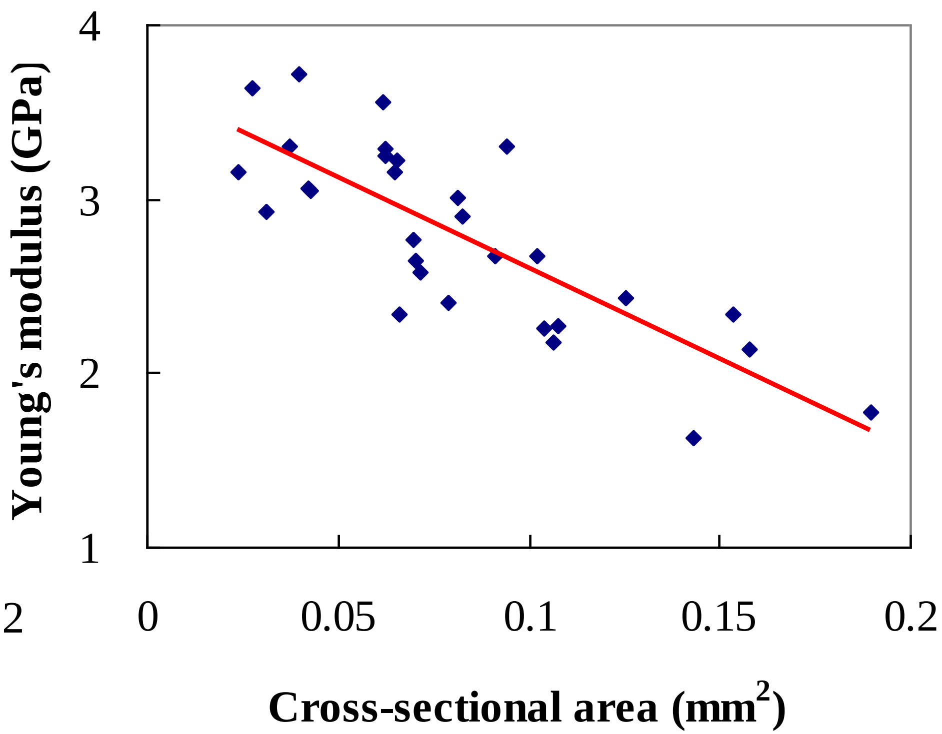
Gauge length: 10 mm
Load cell : 50 N
Tensile speed: 0.5 mm/min

Tran Huu Nam et al., the 7th Asian-Australasian Conference on Composite Materials, 2010.

Tensile properties of untreated coir fibers

Tensile strength (MPa)	Young’s modulus (GPa)	Elongation at break (%)
139.67 ± 39.42	2.79 ± 0.54	29.52 ± 6.89

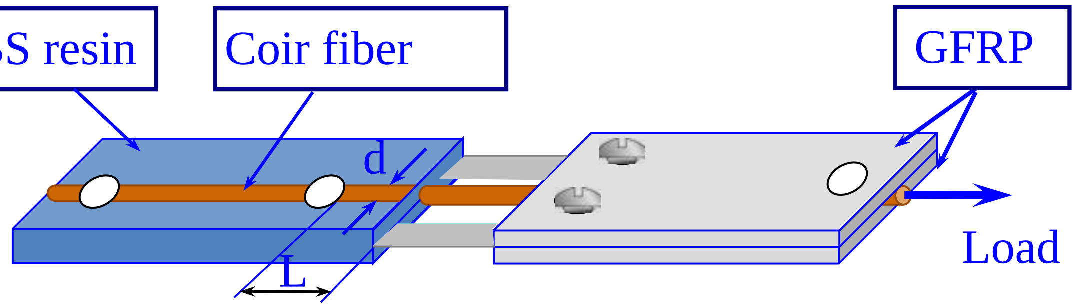




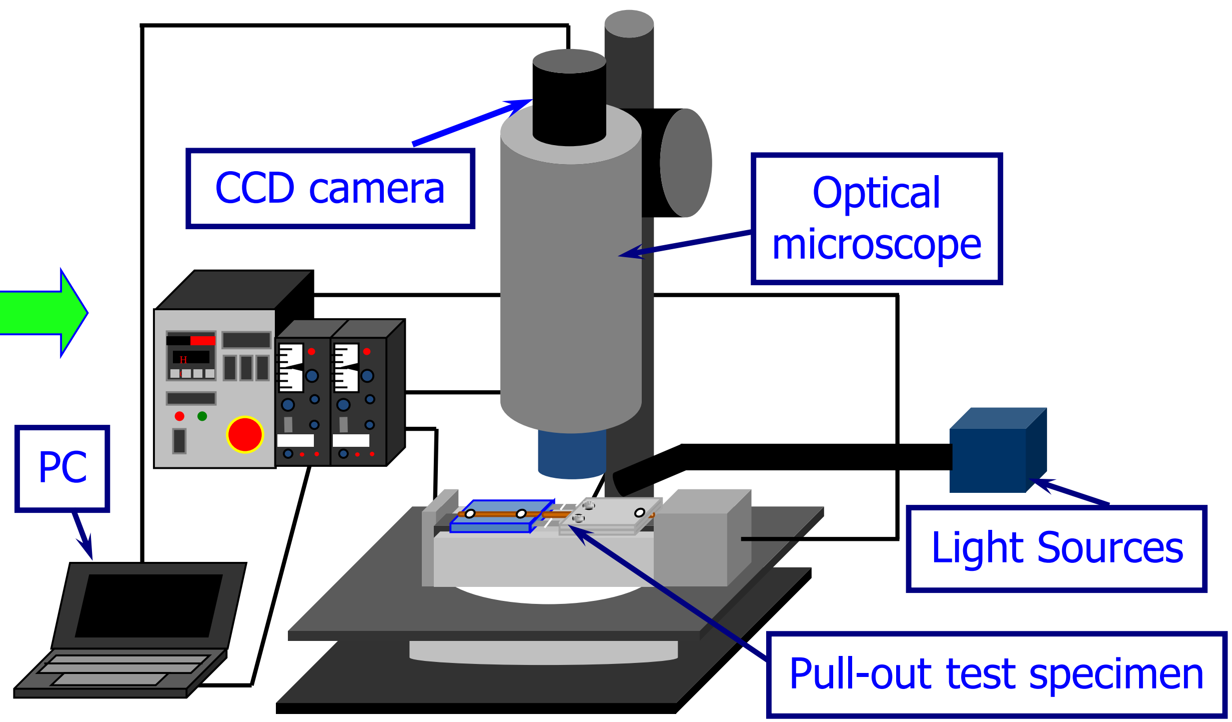
Tran Huu Nam et al., the 7th Asian-Australasian Conference on Composite Materials, 2010.

Single fiber pull-out test

Single fiber pull-out test specimen



Single fiber pull-out test

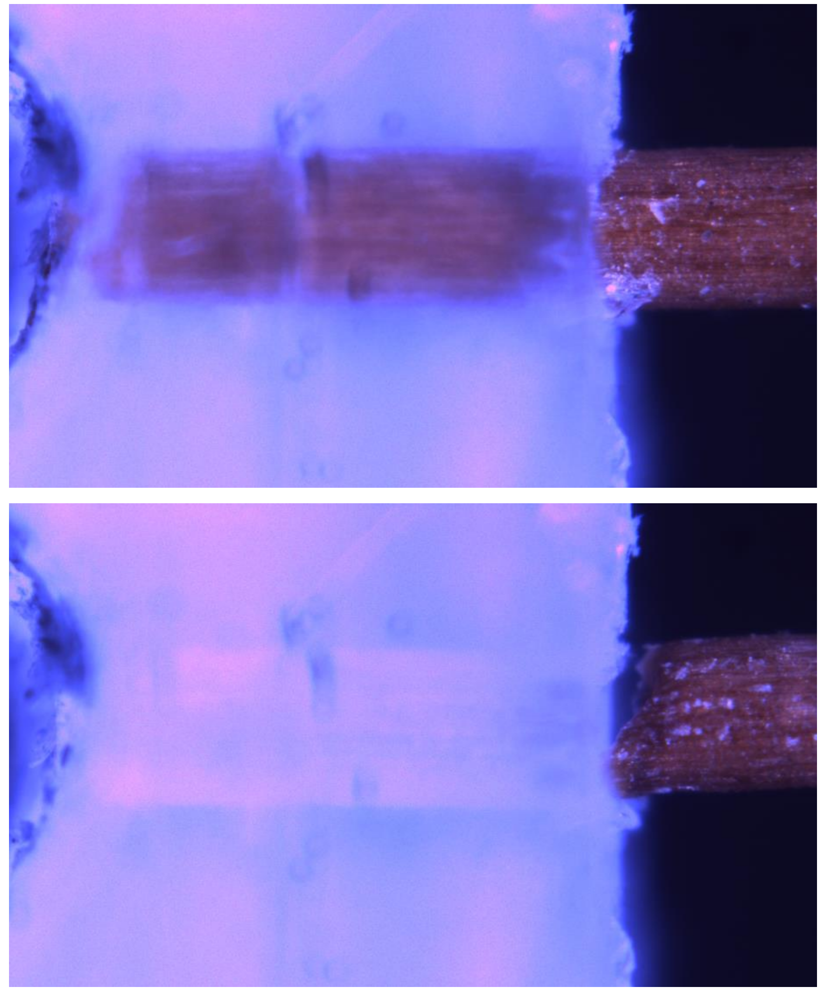


Tran Huu Nam et al., the 7th Asian-Australasian Conference on Composite Materials, 2010.

Single fiber pull-out test

Before single fiber pull-out test

After single fiber pull-out test



Tran Huu Nam et al., the 7th Asian-Australasian Conference on Composite Materials, 2010.

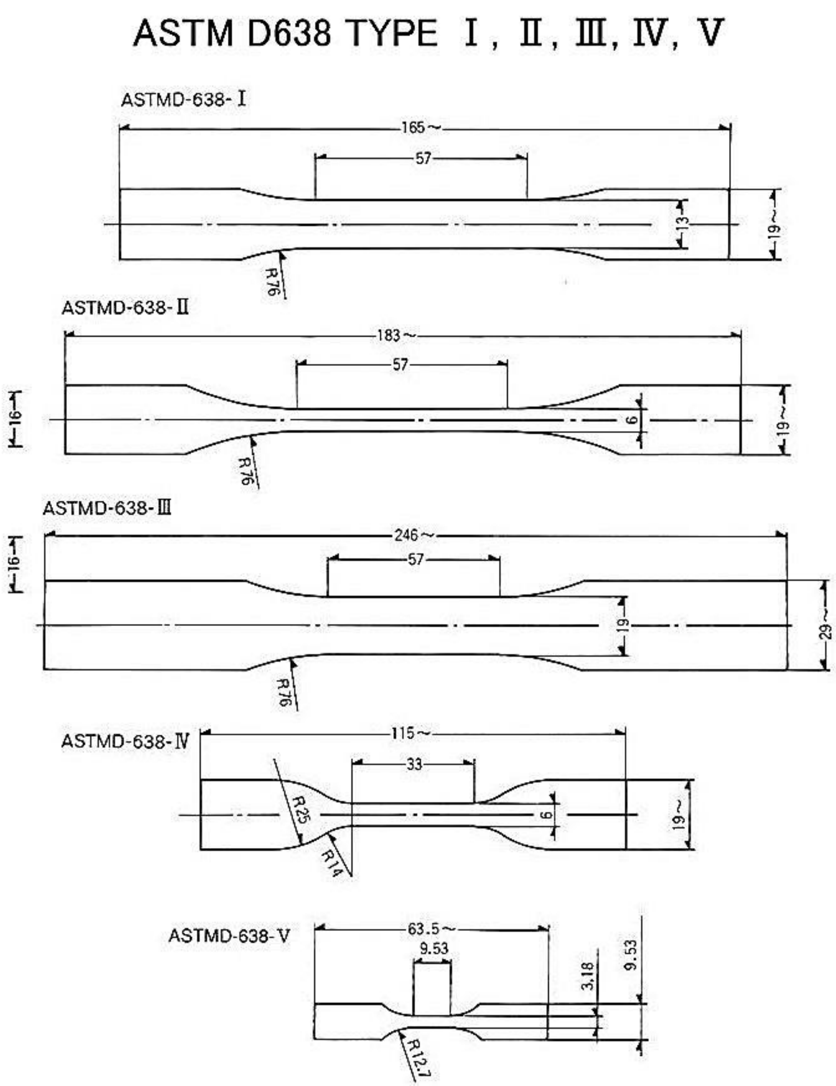
Mechanical testing of matrix

Tension ASTM D 638

Tensile test

Tensile measurement of neat resin properties E_m and $S_{m1}^{(+)}$

The tensile testing machine pulls the sample (dogbone) from both ends and measures the force required to pull the specimen apart and how much the sample stretches before breaking.



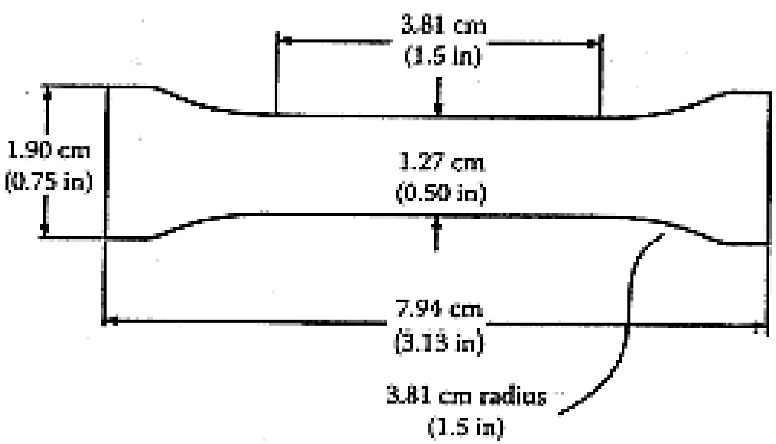
ASTM D638-10 Type I, II, III, IV and V neat resin tensile specimen geometries. (From ASTM Standard D638-10. Copyright ASTM International. Reprinted with permission).

Mechanical testing of matrix

Compression test

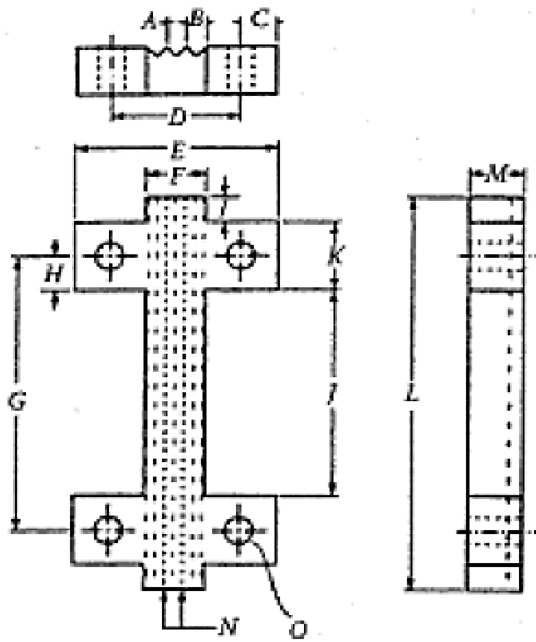
Specimen for measurement of neat resin compressive properties E_m and $S_{m1}^{(-)}$

Compression ASTM D 695



Neat resin compressive test specimen. (From ASTM Standard D695-10. Copyright ASTM International.)

Neat resin compression specimen support jig



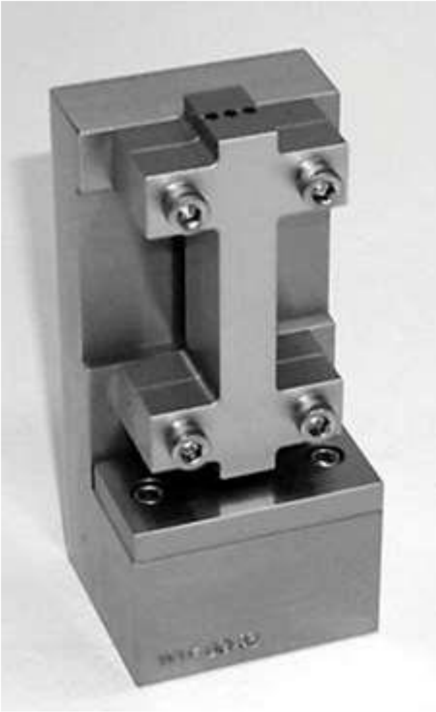
Letter	Metric system	British system
A	0.40 mm	0.0156 in.
B	3.18	0.125
C	6.35	0.250
D	23.8	0.9375
E	36.5	1.4375
F	11.1	0.4375
G	50.8	2.00
H	6.35	0.250
I	4.76	0.1875
J	38.1	1.500
K	12.7	0.500
L	73.0	2.875
M	9.53	0.375
N	3.58	0.141
O	4.76 d.	0.1875 d.

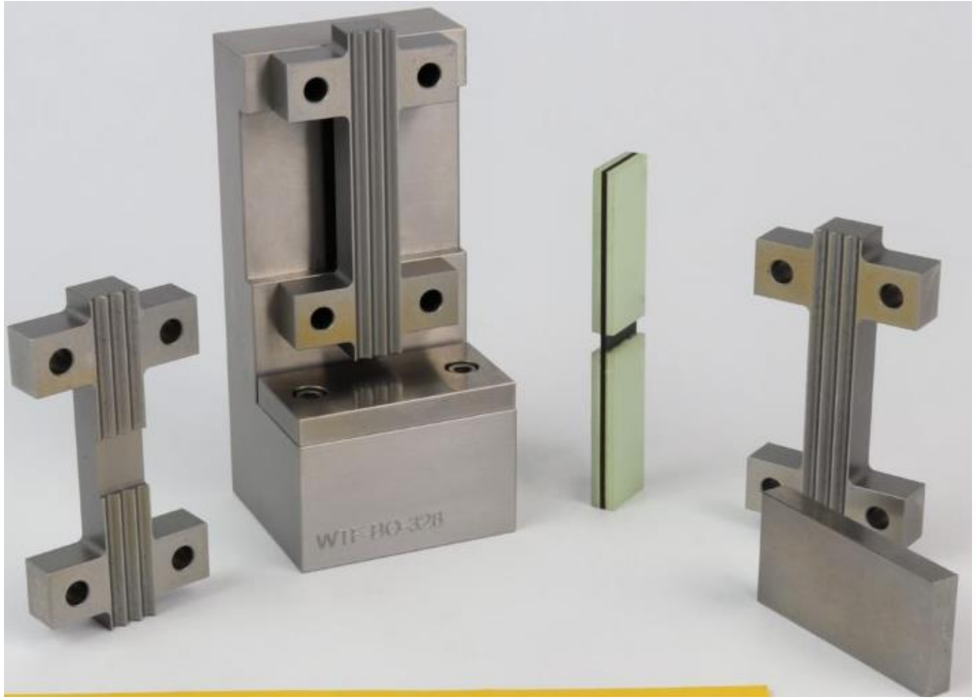
Support jig for D695-10 compressive test specimen. (From ASTM Standard D695-02a. Copyright ASTM International.)

Mechanical testing of matrix

Compression test

Compression test fixture for neat resin specimen





Compression fixture (Modified ASTM D695 Fixture and Base Support)

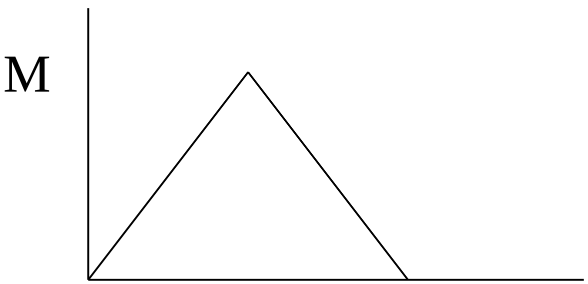
Mechanical testing of matrix

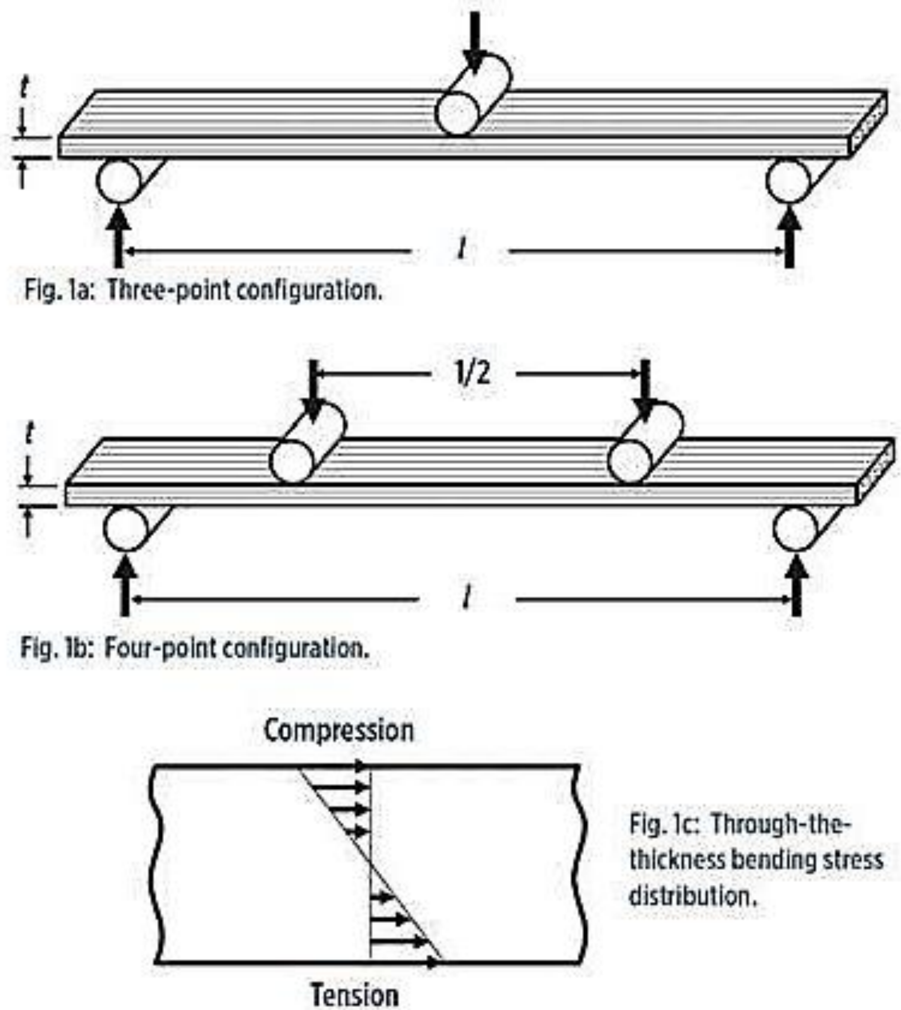
Bending (flexural) test

Three-point and four-point bending test

ASTM Standard D790-10

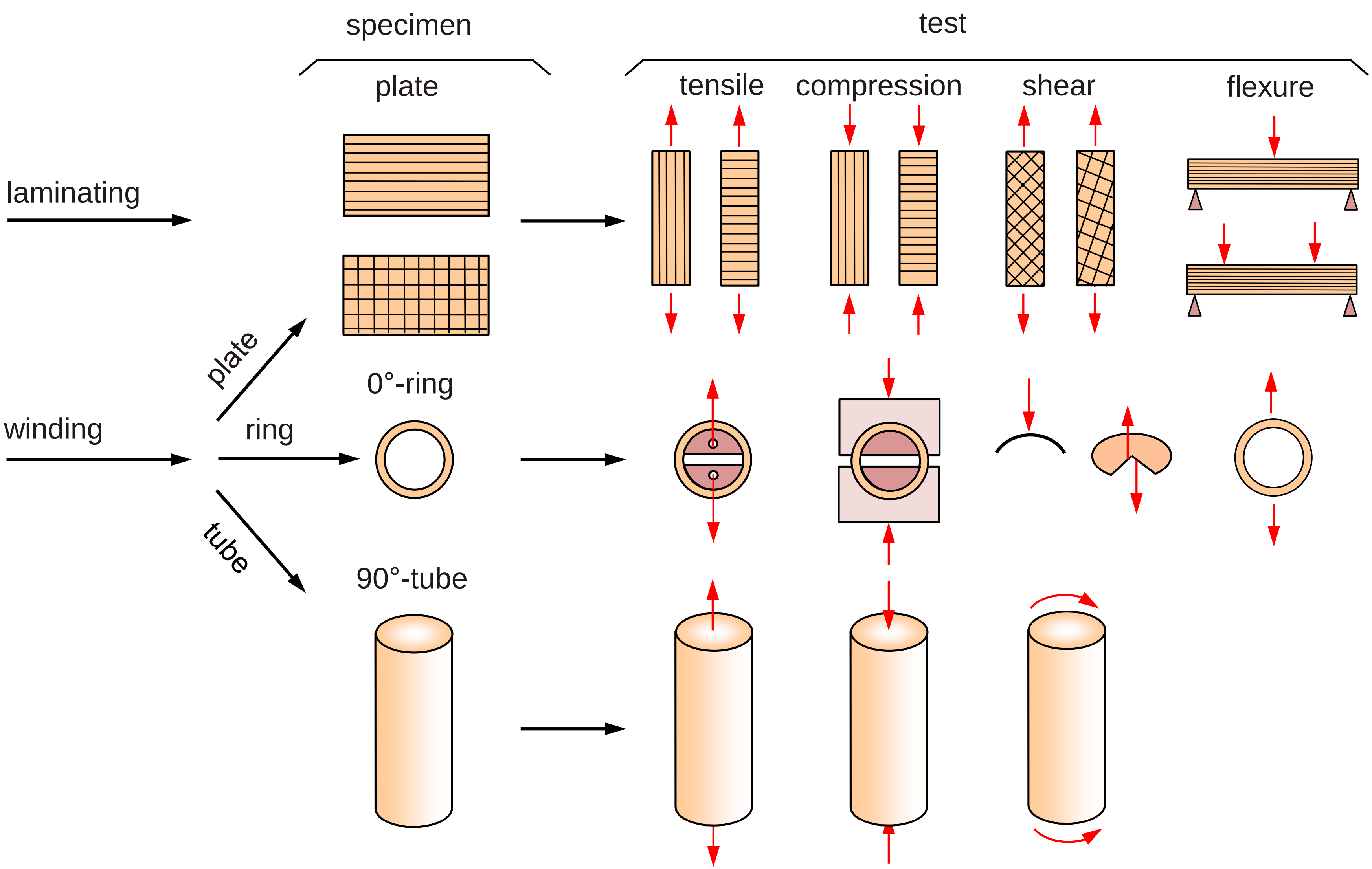
Bending moment diagram





Three-point bending specimen for flexural properties of neat resin or composite. (From ASTM Standard D790-10. Copyright ASTM International.)

6.3. Mechanical testing of lamina and laminate



Unique aspects of testing composite materials

- Orthotropy: different stiffnesses and strengths in different directions.
- Minimum thickness flat plates for testing.
- Properties not always the same in tension and compression.

Elastic properties of composite materials

- Composite Lamina (layer, ply)

  E_1, E_2, E_3

  $\nu_{12}, \nu_{13}, \nu_{23}$

  G_{12}, G_{13}, G_{23}

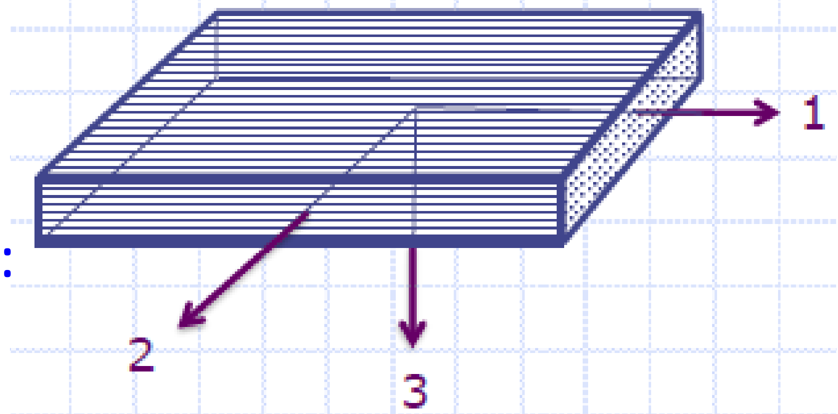
- Transverse Isotropy (5 elastic pro.):

  $E_2 = E_3$

  $\nu_{12} = \nu_{13}$

  $G_{12} = G_{13}$

$$G_{23} = \frac{E_2}{2(1+\nu_{23})}$$



Strength properties of a composite material (Lamina)

Orthotropic lamina (9 strengths):

- 3 Axial Tensile Strengths

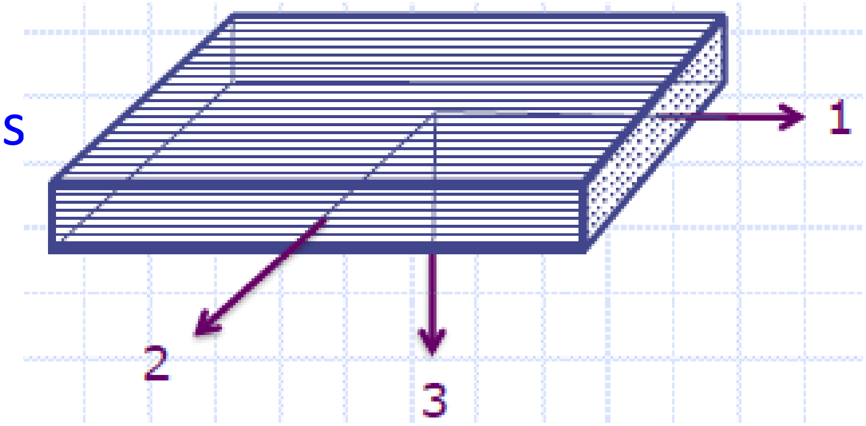
$$S_1^+,\quad S_2^+,\quad S_3^+$$

- 3 Axial Compressive Strengths

$$S_1^-,\quad S_2^-,\quad S_3^-$$

- 3 Shear Strengths

$$S_{12},\quad S_{13},\quad S_{23}$$



Transverse Isotropy (6 strengths):

$S_2 = S_3$

$S_{12} = S_{13}$

Tensile testing of composites

The purpose of the tensile testing is to measure the ultimate tensile strength and modulus of the composite. The standard specimen used for tensile testing of continuous fiber composites is a flat, straight-sided coupon. A flat coupons in ASTM standard D 3039/D 3039M

Tensile strength

$$S^T = \frac{\mathrm{P}_{\max}}{\mathrm{A}}$$

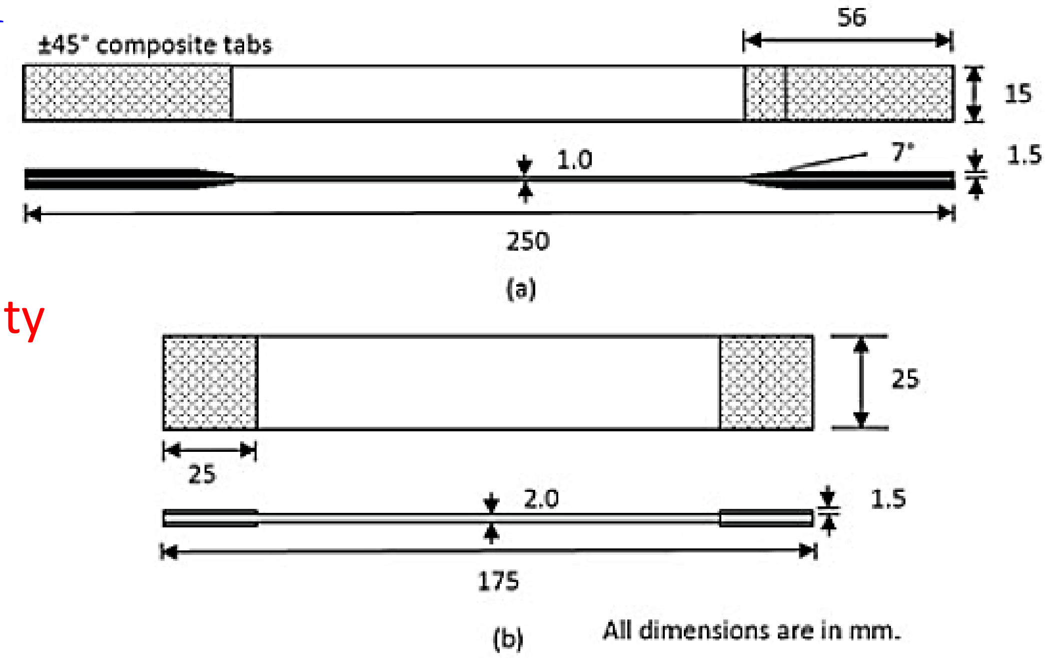
Tensile chord modulus of elasticity

$$E_1 = \frac{\sigma_1^b - \sigma_1^a}{\varepsilon_1^b - \varepsilon_1^a}$$

a. . . 0.1%, b. . . 0.3%

Poisson ratio

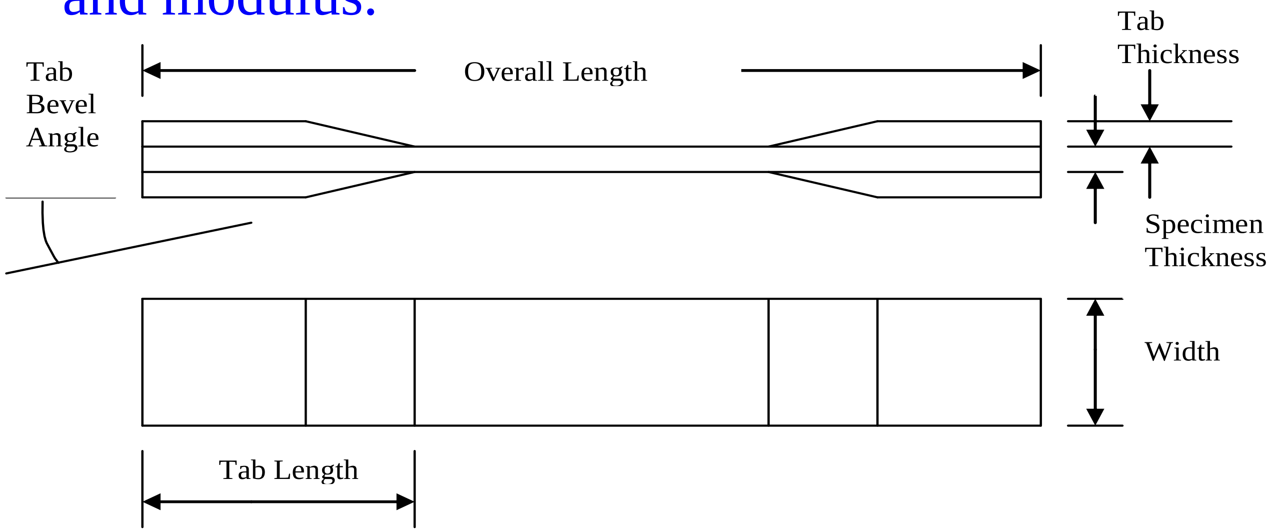
$$\nu = \frac{\Delta\varepsilon_2}{\Delta\varepsilon_1}$$

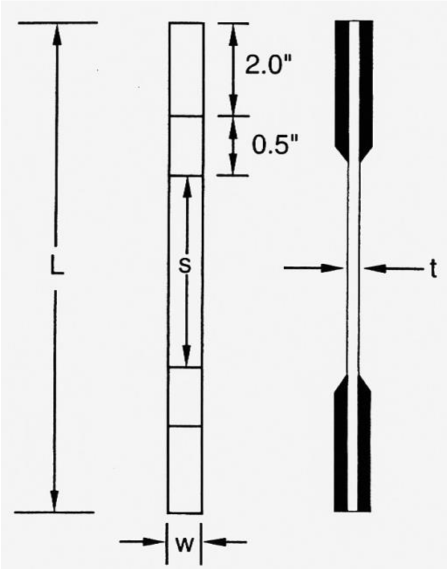


Composite tensile test specimens
(a) ASTM D 3039 for 0° and
(b) ASTM D 3039 for 90°.

Tensile testing for flat specimens: Size and standard

Composite tensile specimen for measurement of ultimate tensile strength and modulus.



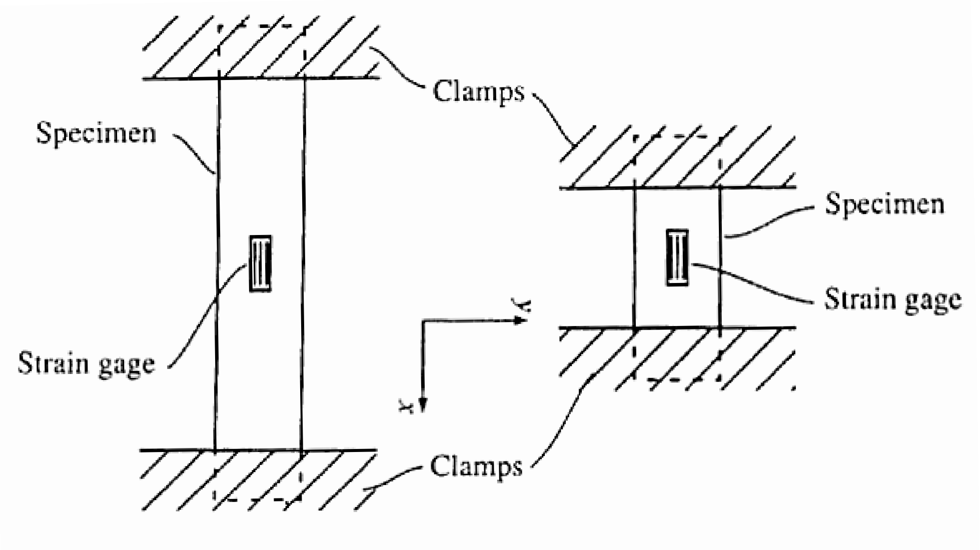


ASTM D3039/D3039M–17 standard tensile test.

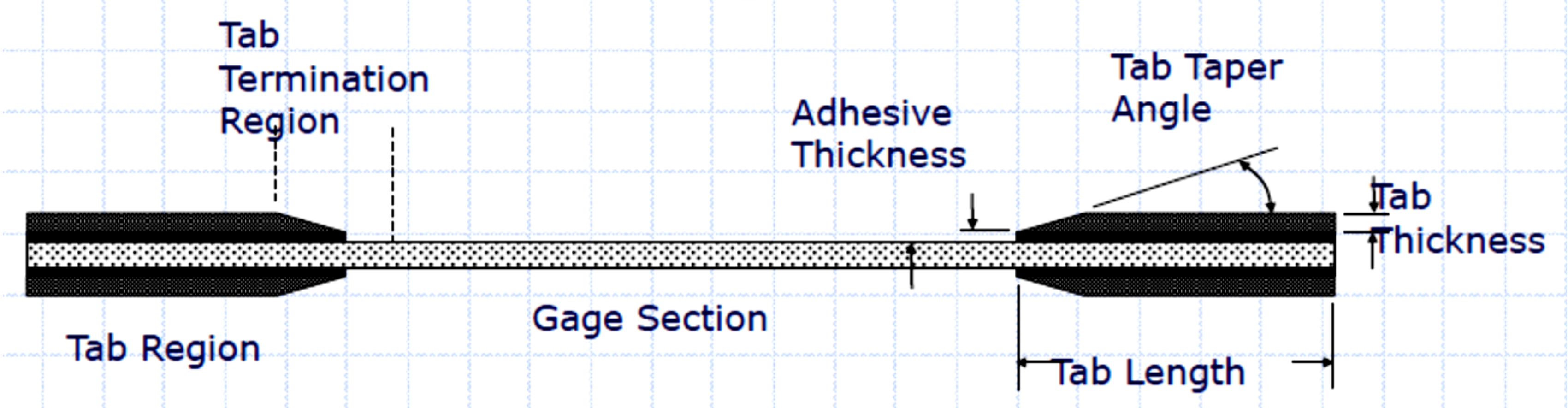
Fiber Orientation	Width, mm [in.]	Overall Length, mm [in.]	Thickness, mm [in.]	Tab Length, mm [in.]	Tab Thickness, mm [in.]	Tab Bevel Angle,°
0° unidirectional	15 [0.5]	250 [10.0]	1.0 [0.040]	56 [2.25]	1.5 [0.062]	7 or 90
90° unidirectional	25 [1.0]	175 [7.0]	2.0 [0.080]	25 [1.0]	1.5 [0.062]	90
balanced and symmetric	25 [1.0]	250 [10.0]	2.5 [0.100]	emery cloth	—	—
random-discontinuous	25 [1.0]	250 [10.0]	2.5 [0.100]	emery cloth	—	—

Tensile testing for flat specimens: Measurement of strain

- Straight-sided specimens
- Adhesively bonded tabs
- Strain gages (or extensometer) to measure axial and transverse strain (for E, ν_{12})
- Requires valid gage section failure



(a) Long, slender specimen (b) Short, wide specimen



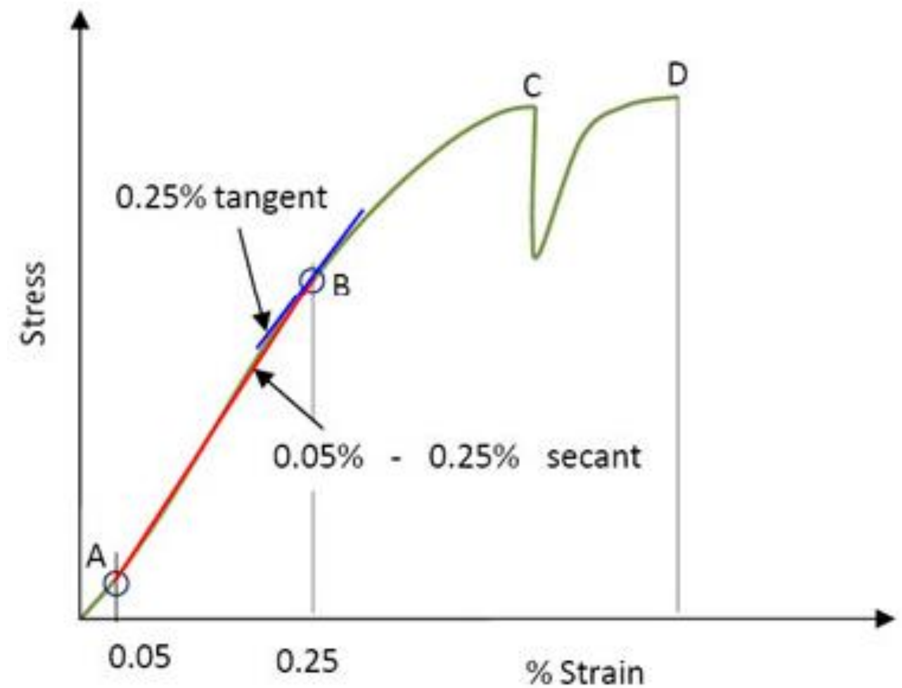
Tensile testing for flat specimens: Measurement of Modulus

Due to progressive damage the stiffness of the lamina or laminae/laminate changes causing the stress strain curve to be non-linear. The measurement of modulus in a tensile testing from a non-linear loading curve can be done by three methods.

The first method: the modulus is taken as a tangent to the initial part of the curve (Point A).

The second method: a tangent is constructed at a specified strain level. For example, the modulus is measured at 0.25% strain or 0.0025 strain (Point B).

The third method: a secant is constructed between two points. For example, a secant is constructed between points A and B. Typically, the strain values at these points are 0.0005 and 0.0025. In ASTM standards the secant is called as *chord*.



Typical tensile stress-strain curve with details

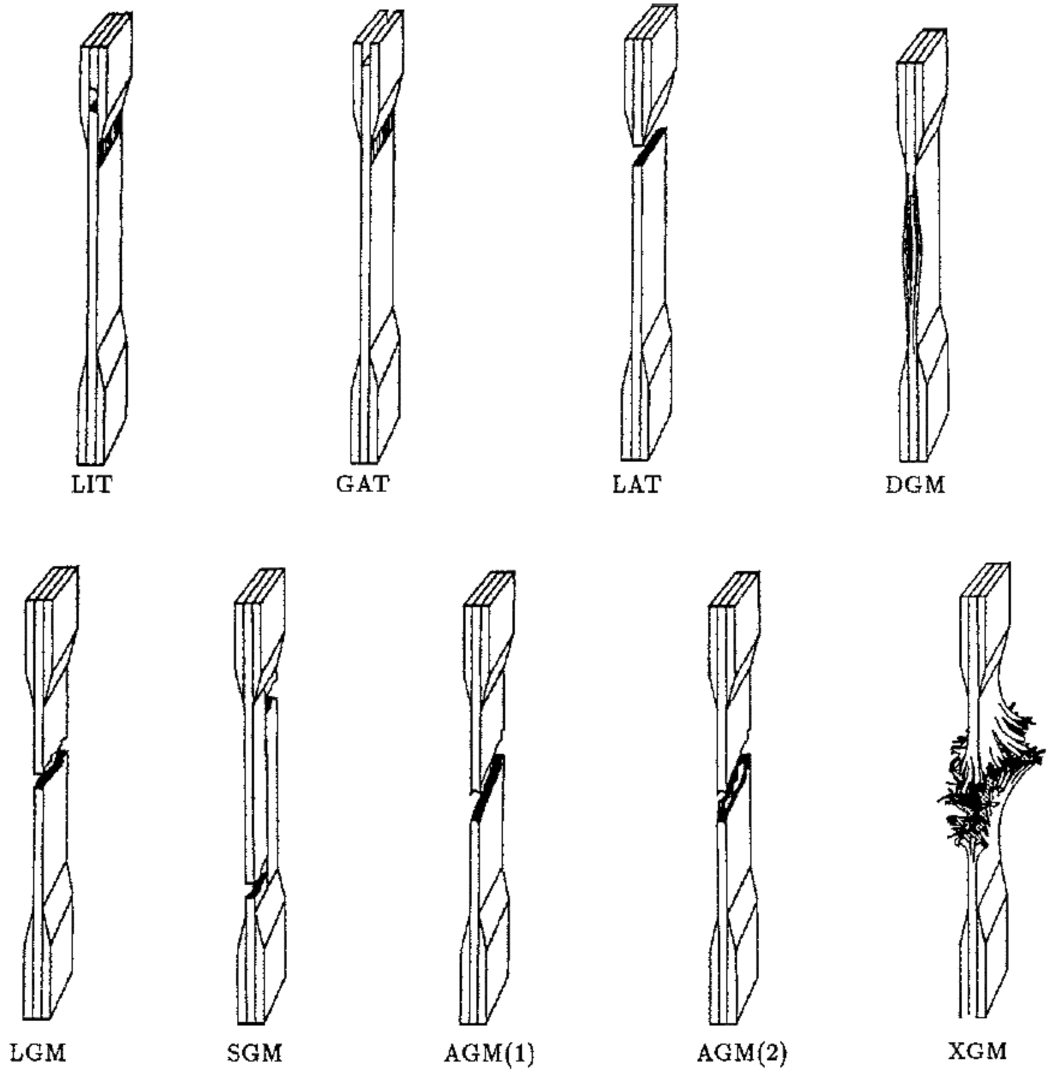
The modulus measured by these methods is known as ***'initial tangent modulus'***, ***'B% modulus'*** **and** ***'A%-B% secant (chord) modulus'***.

6.3. Mechanical testing of lamina and laminate

Tensile testing for flat specimens: Tensile Test Failure Code

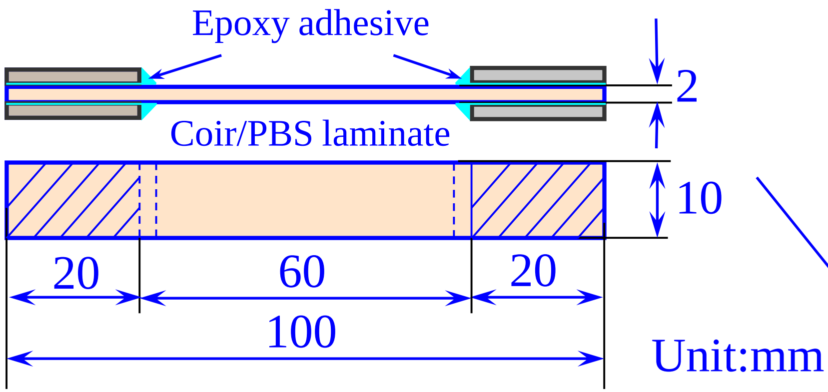
Tensile Test Failure Code/
Typical Mode ASTM D 3039

Type	Code	Area	Code	Location	Code
Angled	A	Inside grip	I	Bottom	B
edge Delam.	D	At grip	A	Top	T
Grip/tab	G	< 1W from grip	W	Left	L
Lateral	L	Gage	G	Right	R
Multi–mode	M	Multiple areas	M	Middle	M
long.–Splitting	S	Various	V	Various	V
eXplosive	X	Unknown	U	Unknown	U
Other	O				



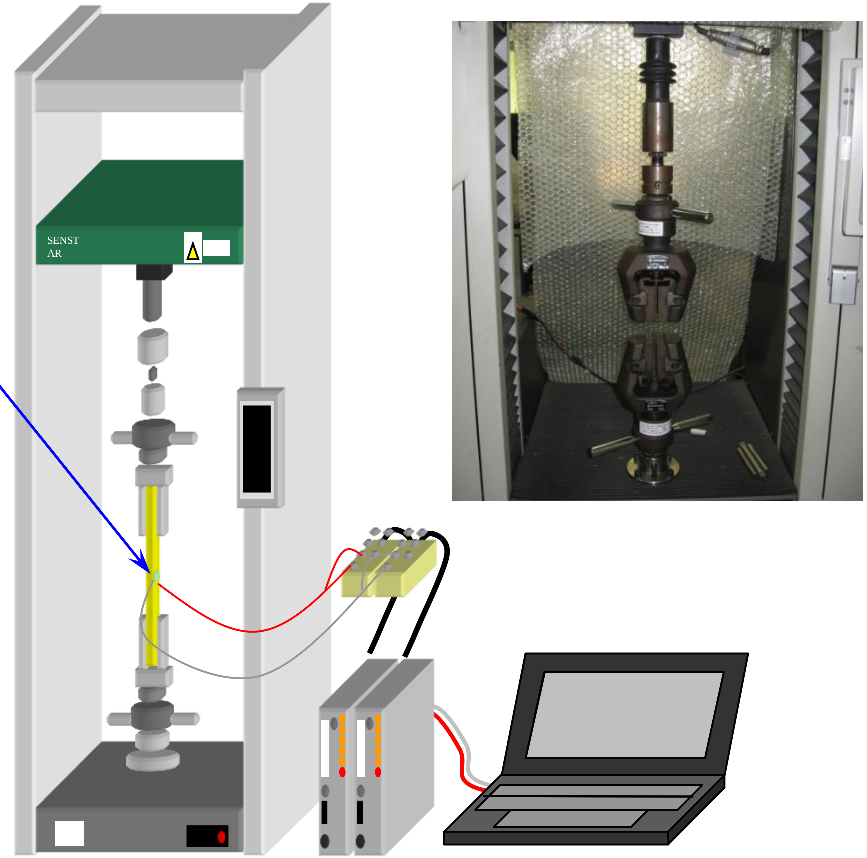
6.3. Mechanical testing of lamina and laminate

Tensile specimen



Specimen length: 100 mm
Gauge length: 50 mm.
Crosshead speed: 0.5 mm/min.
Strain gauges embedded at the specimen center (KFEL-5-120-C1L1M2R, KFEL-2-120-C1L1M2R)
Epoxy adhesive: Araldite standard

Universal testing machine

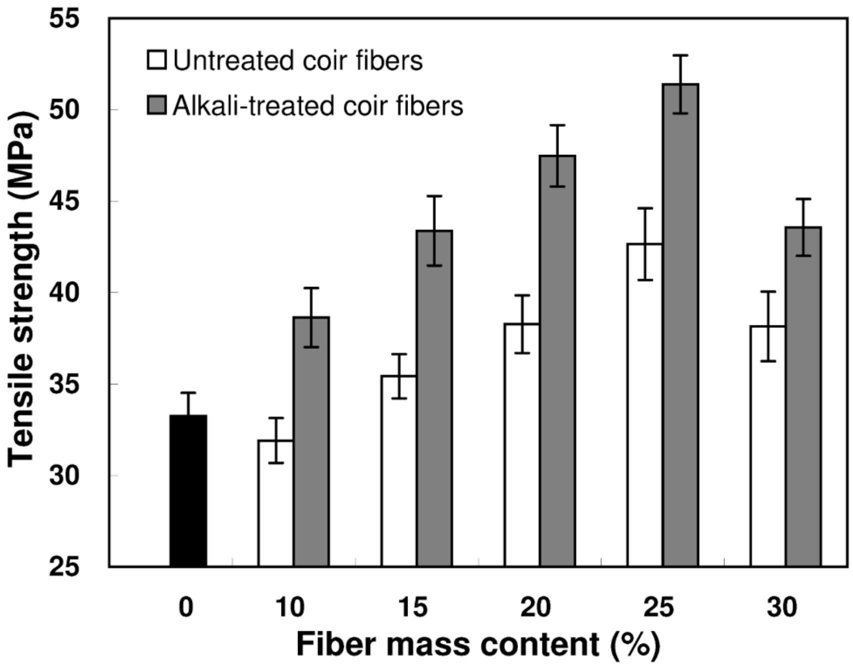


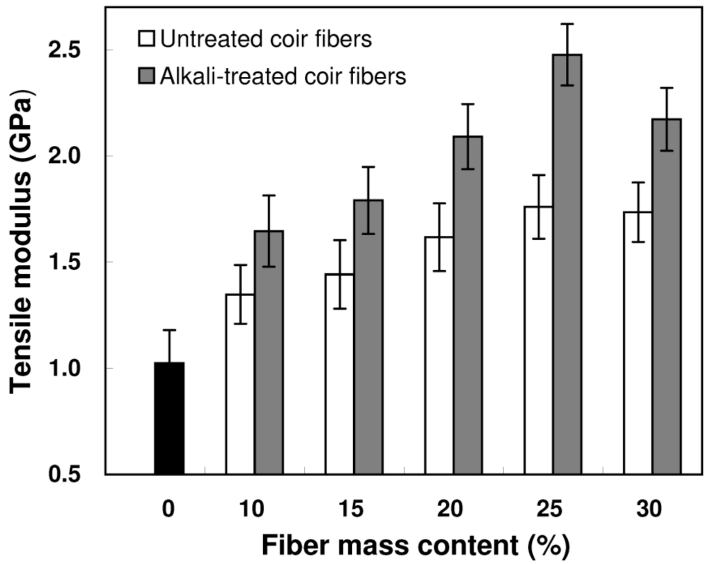
SENSTAR SC-5H (5000N)

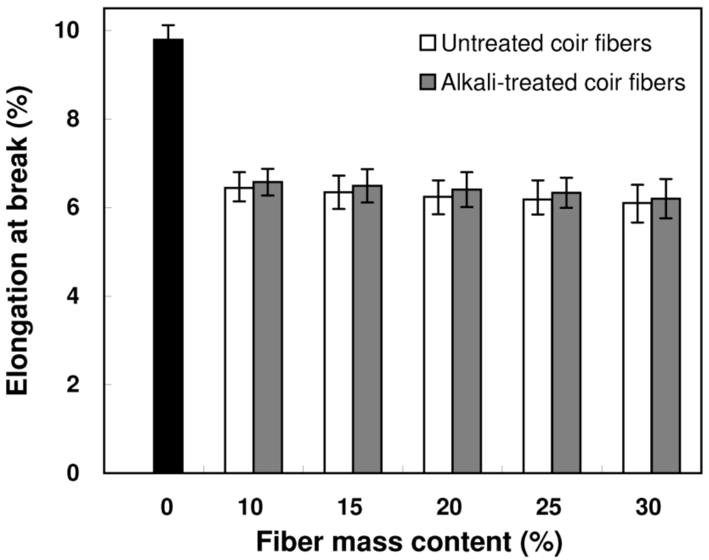
Dynamic strain measurement DPM-601A

Tran Huu Nam, et al. Effect of alkali treatment on interfacial and mechanical properties of coir fiber reinforced poly (butylene succinate) biodegradable composites. *Composites Part B: Engineering*, 42(6):1648-1656, 2011.

Tensile Properties of Coir fiber reinforced PBS composites





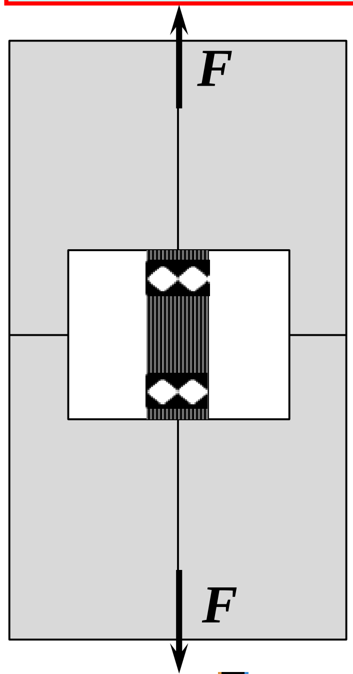


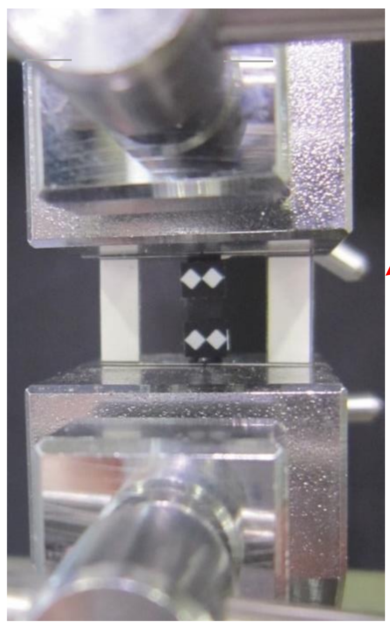
Tran Huu Nam et al. Effect of alkali treatment on interfacial and mechanical properties of coir fiber reinforced poly (butylene succinate) biodegradable composites. *Composites Part B: Engineering*, 42(6):1648-1656, 2011.

6.3. Mechanical testing of lamina and laminate

Tensile testing for flat specimens

Specimen length: 20-30 mm
Specimen width: 3 mm
Gauge length: 10 mm
Crosshead speed: 0.1 mm/min





Stress: $\sigma = \frac{F}{A}$ **Elastic modulus:** $E = \frac{\sigma}{\varepsilon}$

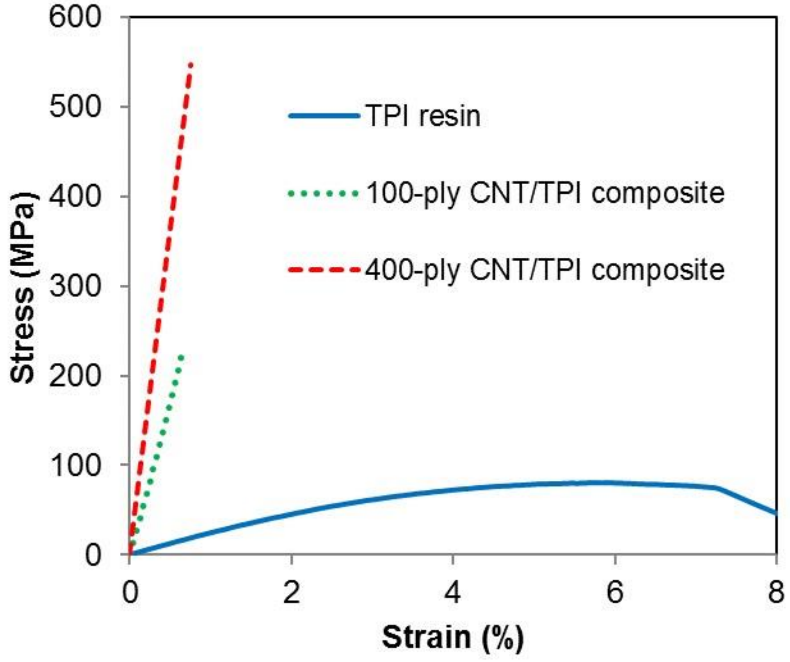
Tensile testing machine

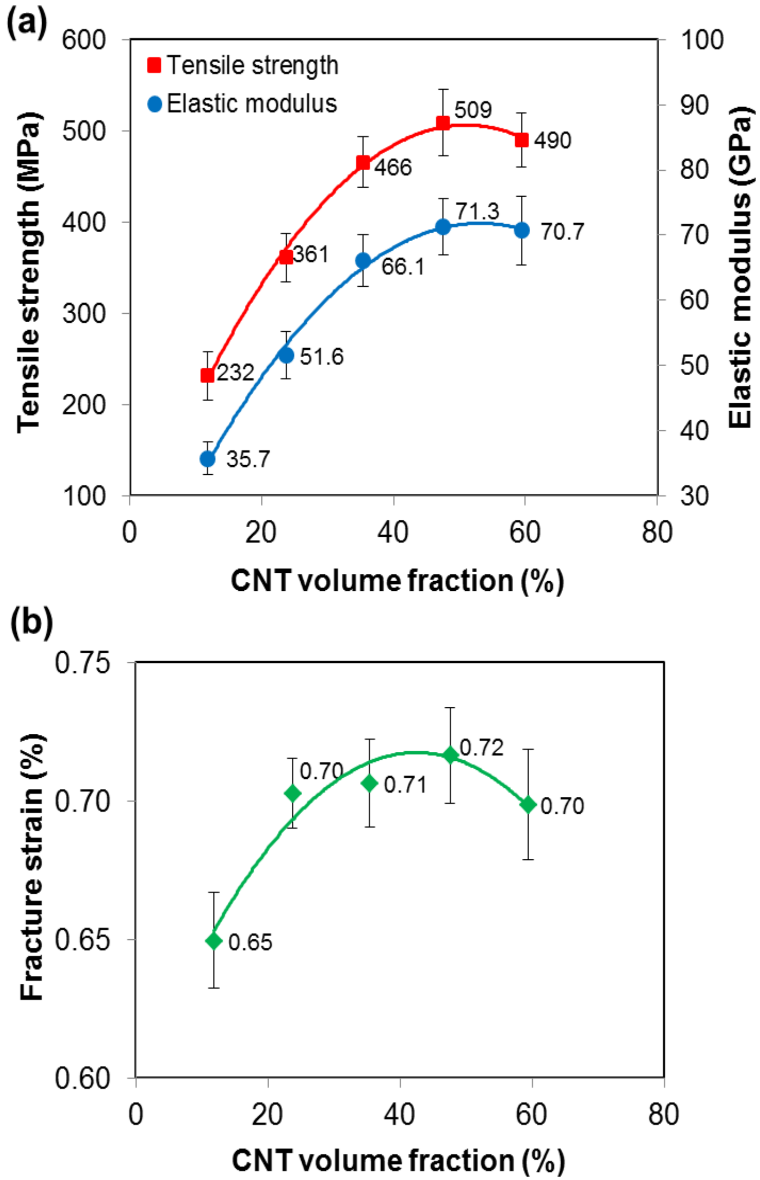
Shimadzu EZ-TEST 500N

Tran Huu Nam et al. Journal of Composite Materials, 53(9), 2018.

Tensile testing for flat specimens:

Typical stress and strain curve





CNT: carbon nanotube;
TPI: thermoplastic polyimide.

Tran Huu Nam et al. Improved mechanical properties of aligned multi-walled carbon nanotube/thermoplastic polyimide composites by hot stretching. Journal of Composite Materials, 53(9), 2018.

Compression testing

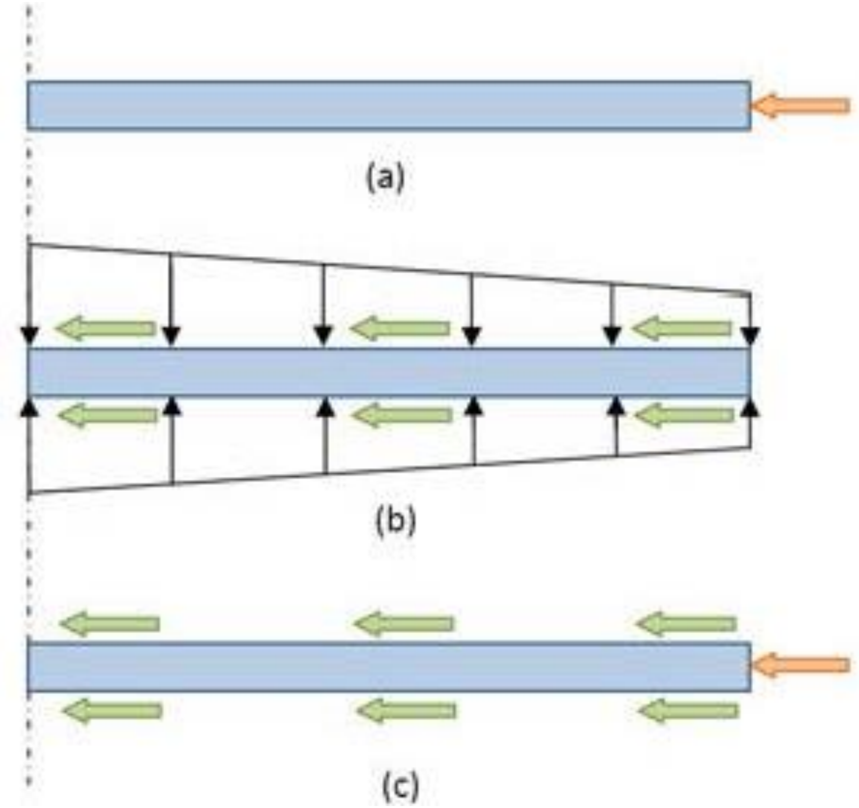
- There are three ways of imposing the loads for compression testing.
- Many test methods have been developed. Depending on the way the load is applied, the characterization is performed by the following methods: End Loading, Shear Loading, and Combined Loading Methods.

Compressive strength ~ σ_{max}

$$S^c = \frac{P_{max}}{A}$$

Compressive modulus of elasticity

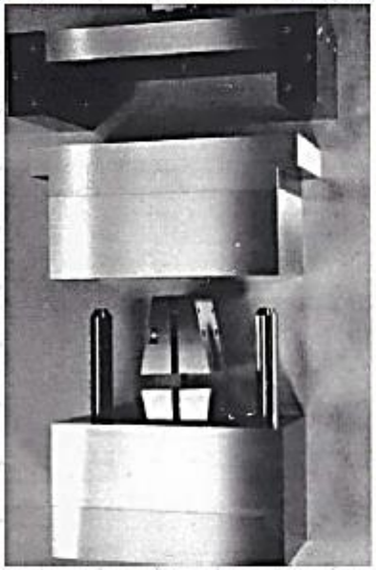
$$E_1 = \frac{\Delta\sigma}{\Delta\varepsilon}$$

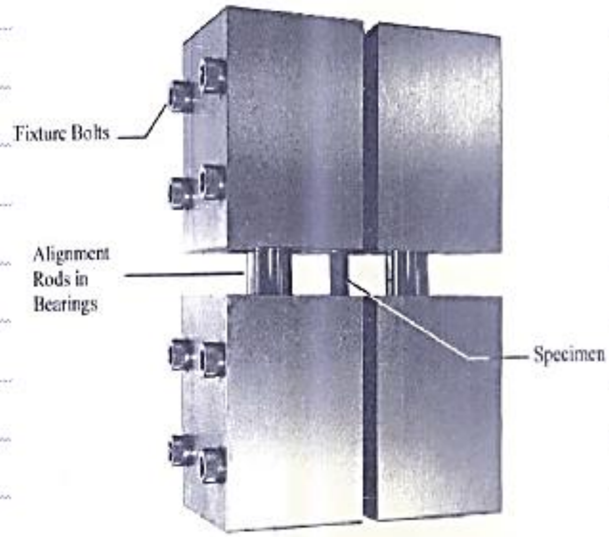


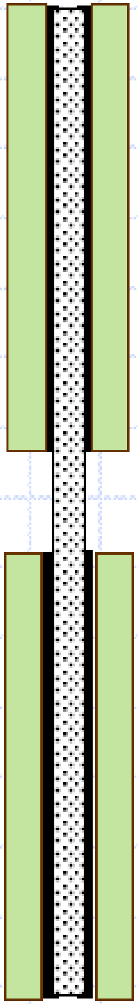
Load imposition methods for compression testing: (a) Direct end loading, (b) Shear loading, and (c) Mixed shear and direct end loading

Compression testing

Common Compression Test Methods







Shear loading

ASTM D 3410

- 5.5 in. long specimen
- 0.5 in. gage length
- Versatile
- Heavy and expensive

End loading

Modified ASTM D 695

- 3.18 in. long specimen
- 0.188 in. gage length
- Separate tests for modulus (untabbed) and strength (tabbed)

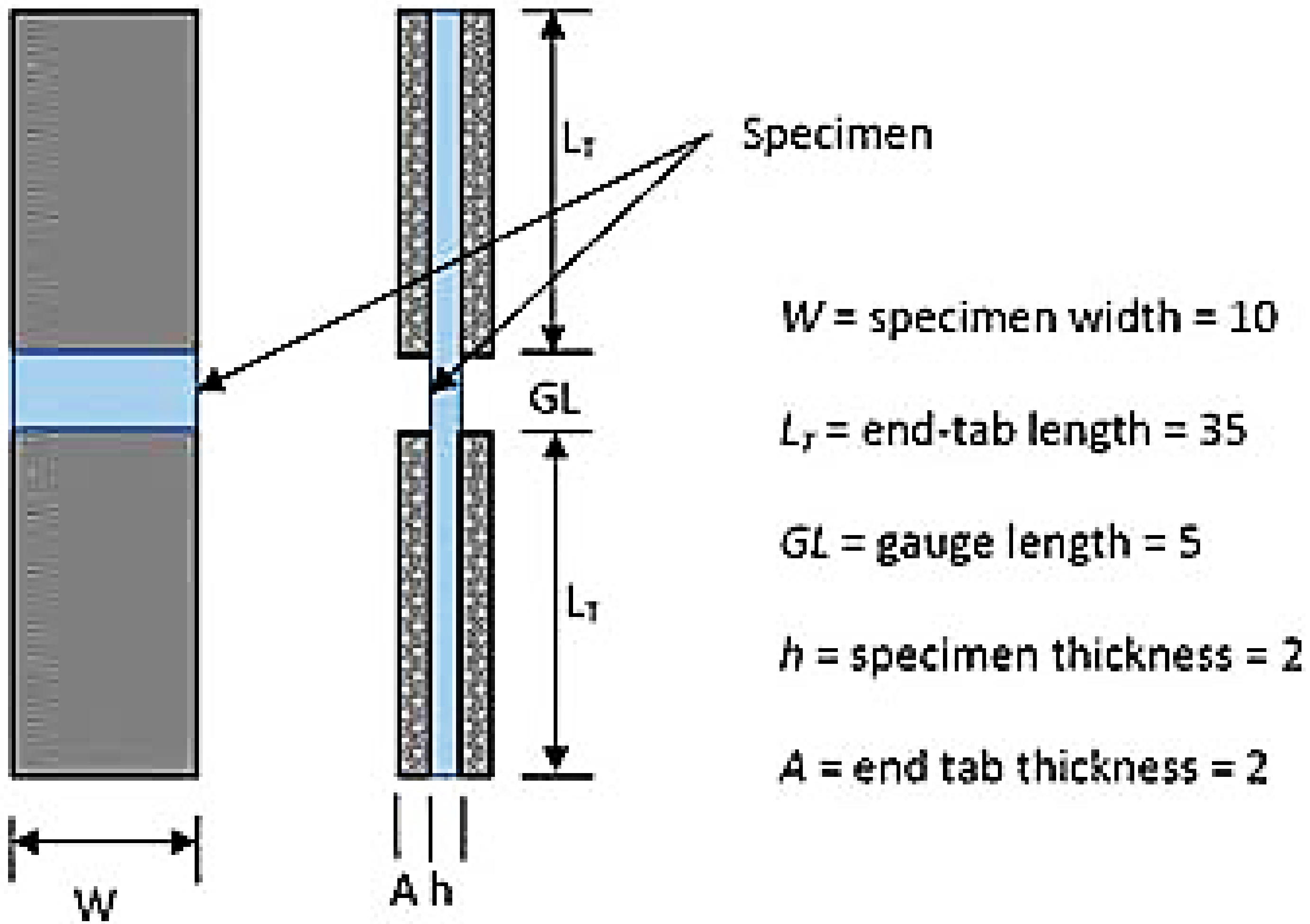
Combined loading

ASTM D 6641

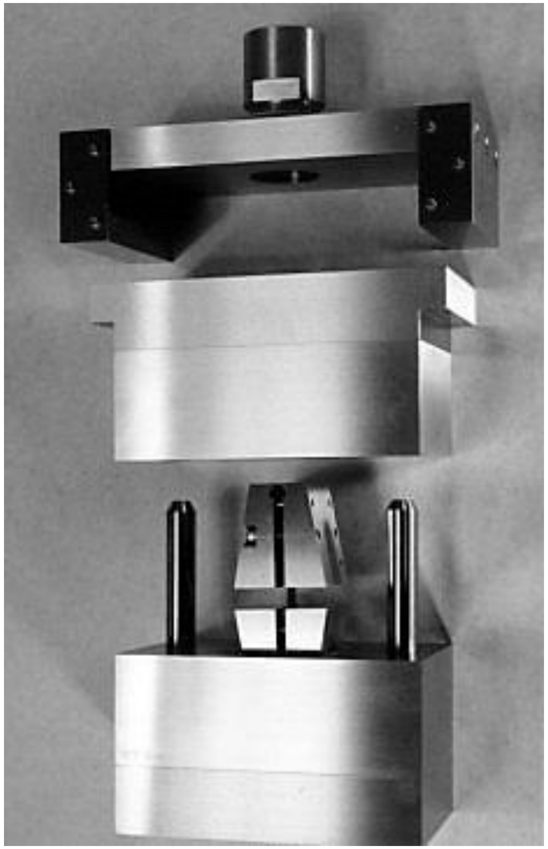
- 5.5 in. long specimen
- 0.5 in. gage length
- Adjustable loading ratio via bolt torque

Compression testing

Composite compression test specimen according to ASTM D695 (modified) standard.

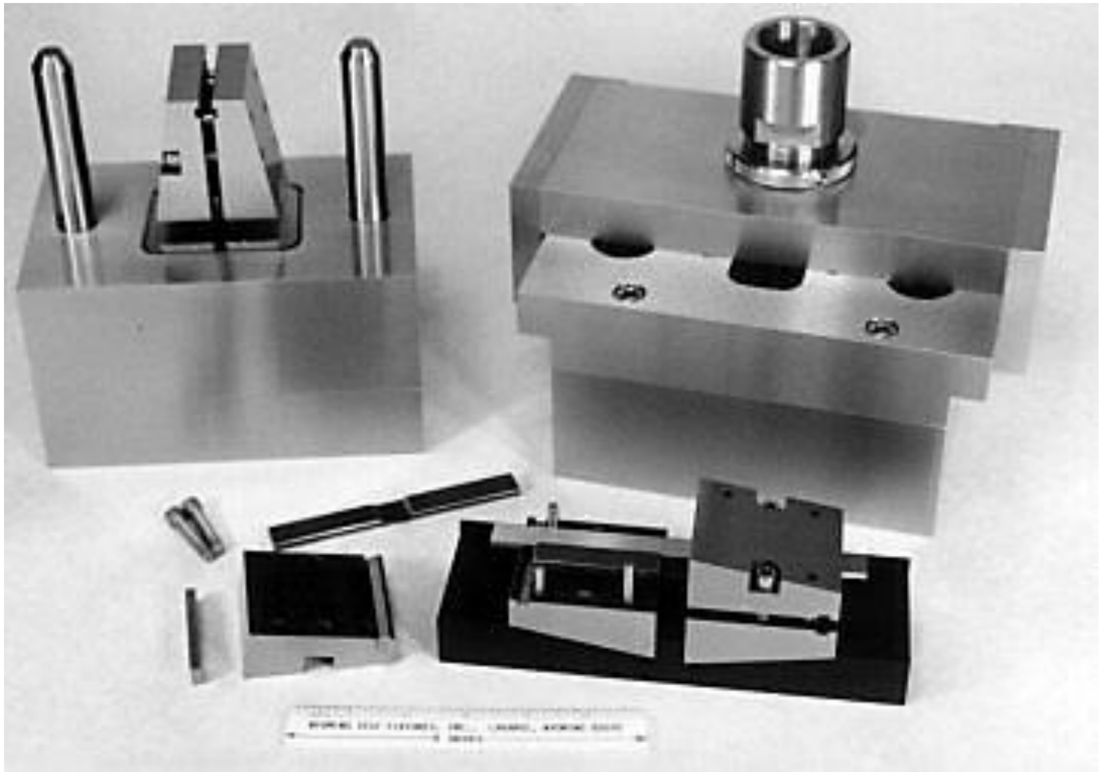


Compression testing



Shear loading method

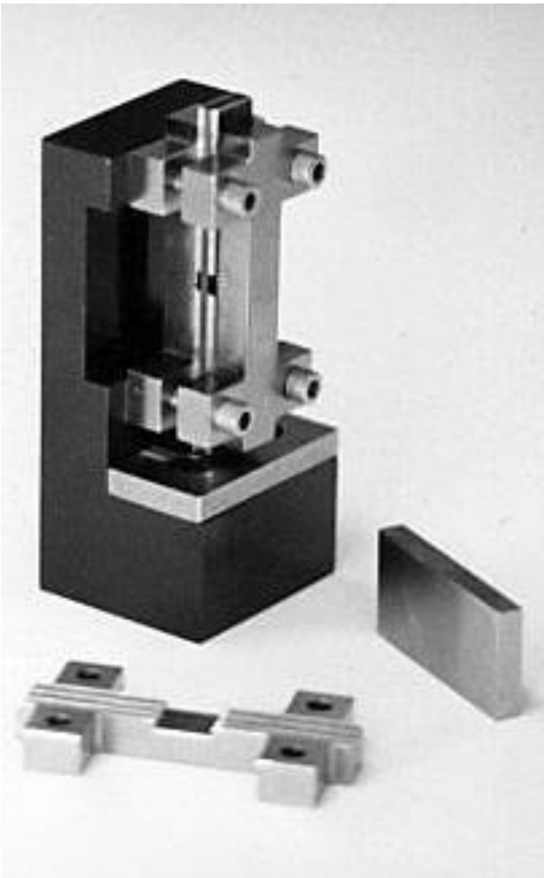
IITRI compression test (ASTM D 3410)

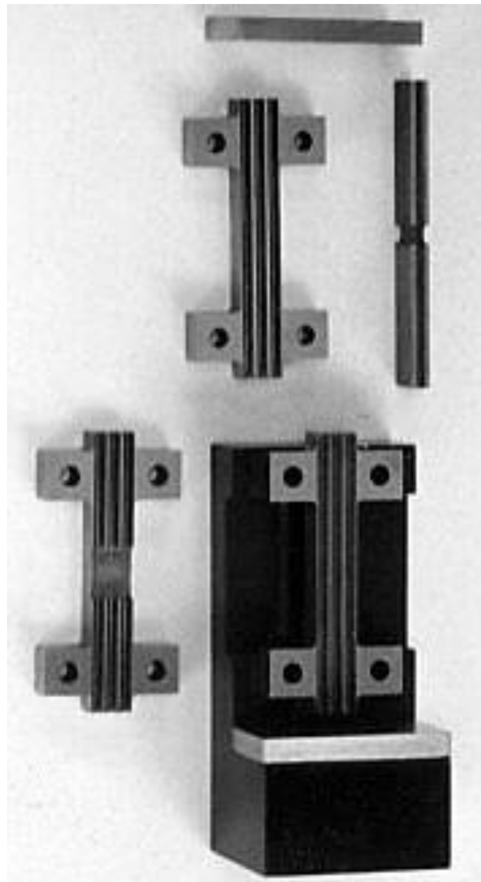


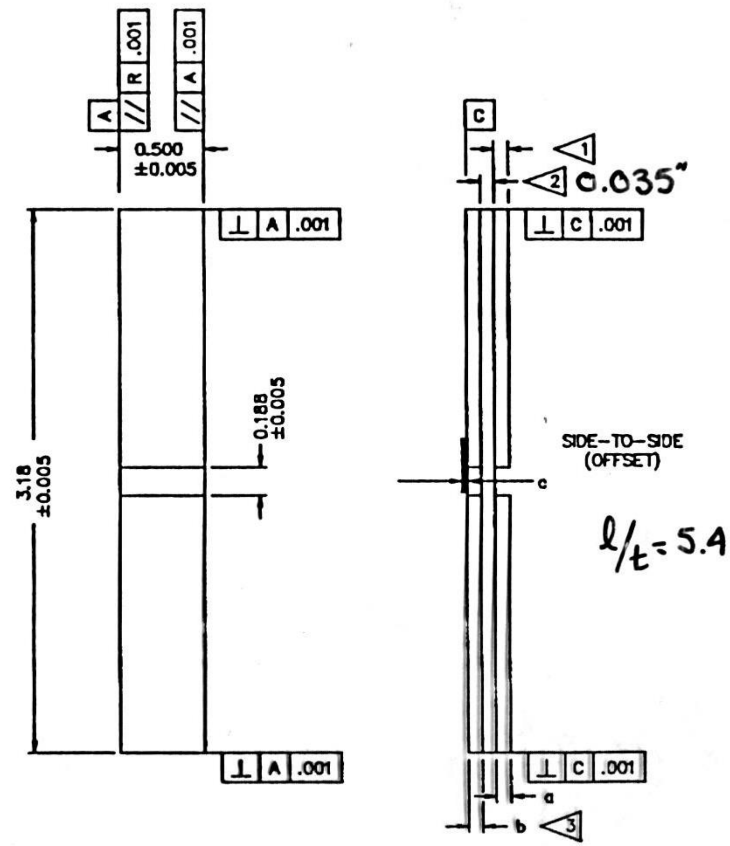
Advantages: Alignment; high data averages and low scatter; large specimens possible

Disadvantages: Expense; specimen tabbing & machining critical; tab s-concentration

Compression testing End loading method: Modified ASTM D 695







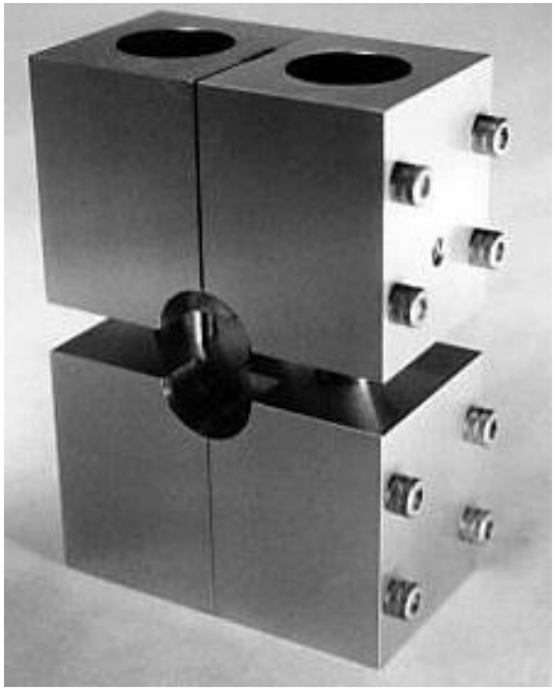
Advantages: Small, thin specimen; reduced material; highly supported against buckling

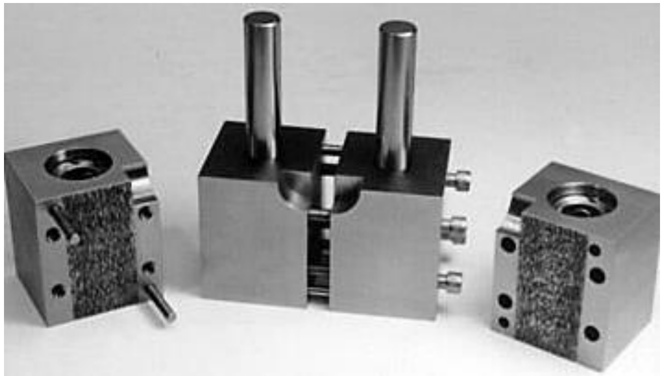
Disadvantages: No stress-strain curve because there is not enough room to install a strain gage; untabbed for modulus; tabbed for strength; tab s-concentration

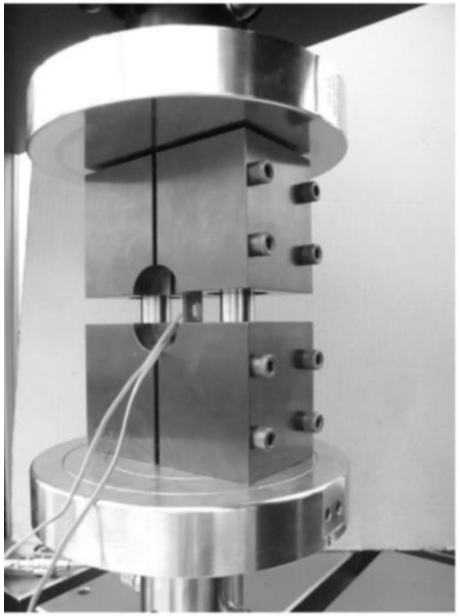
6.3. Mechanical testing of lamina and laminate

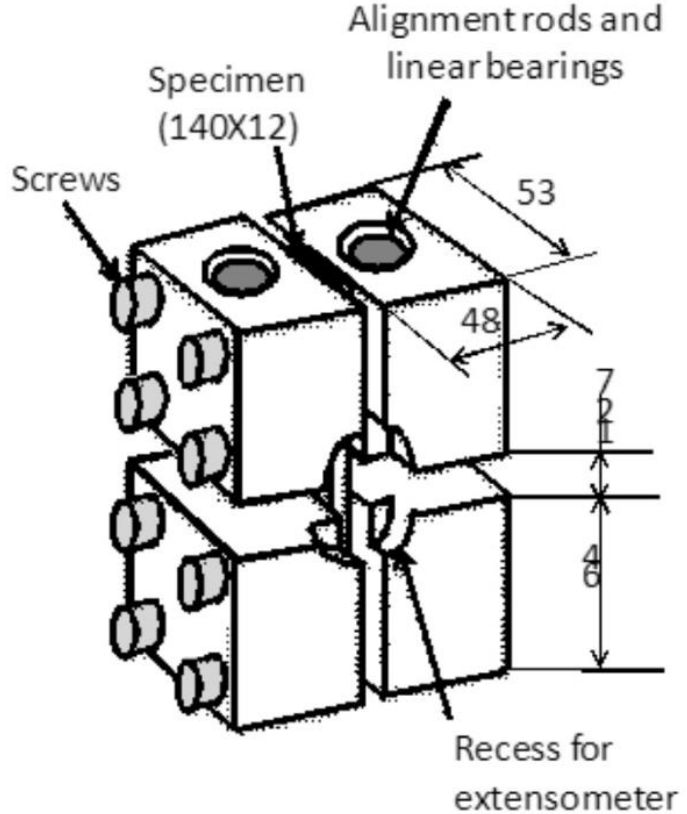
Compression testing

Combined loading method: ASTM D 6641









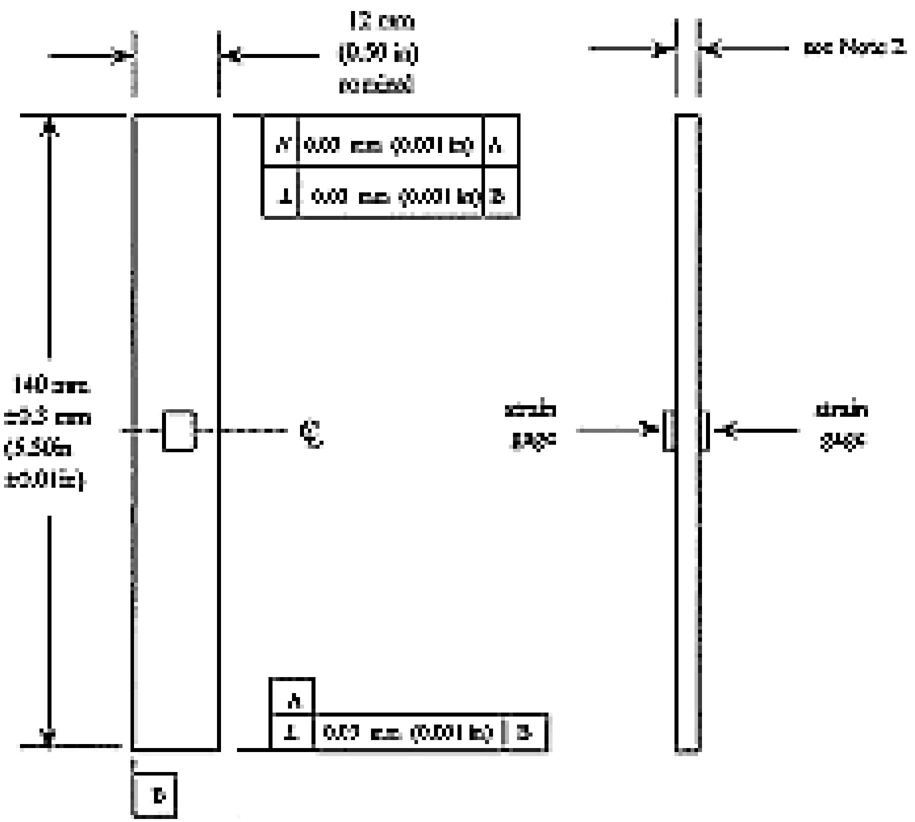
Advantages: No tabbing required; simple fixture; inexpensive; simple alignment; some shear loading

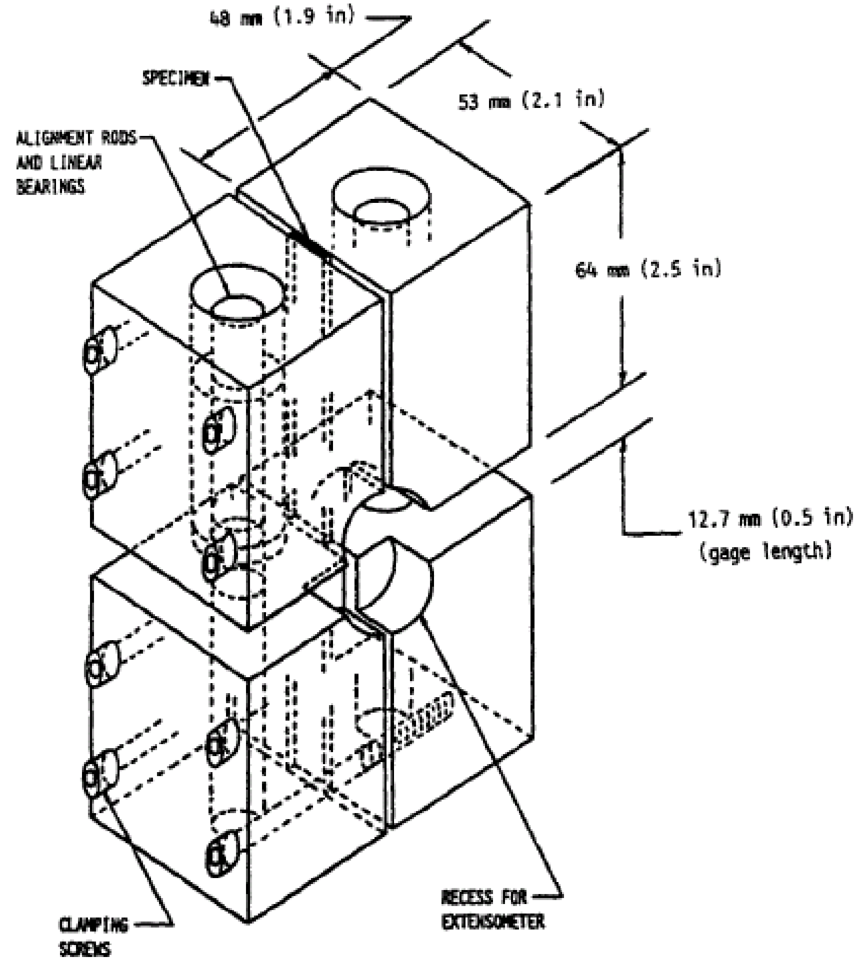
Disadvantages: End crushing for highly orthotropic specimens; support s-concentration; specimen tolerances critical

6.3. Mechanical testing of lamina and laminate

Compression testing

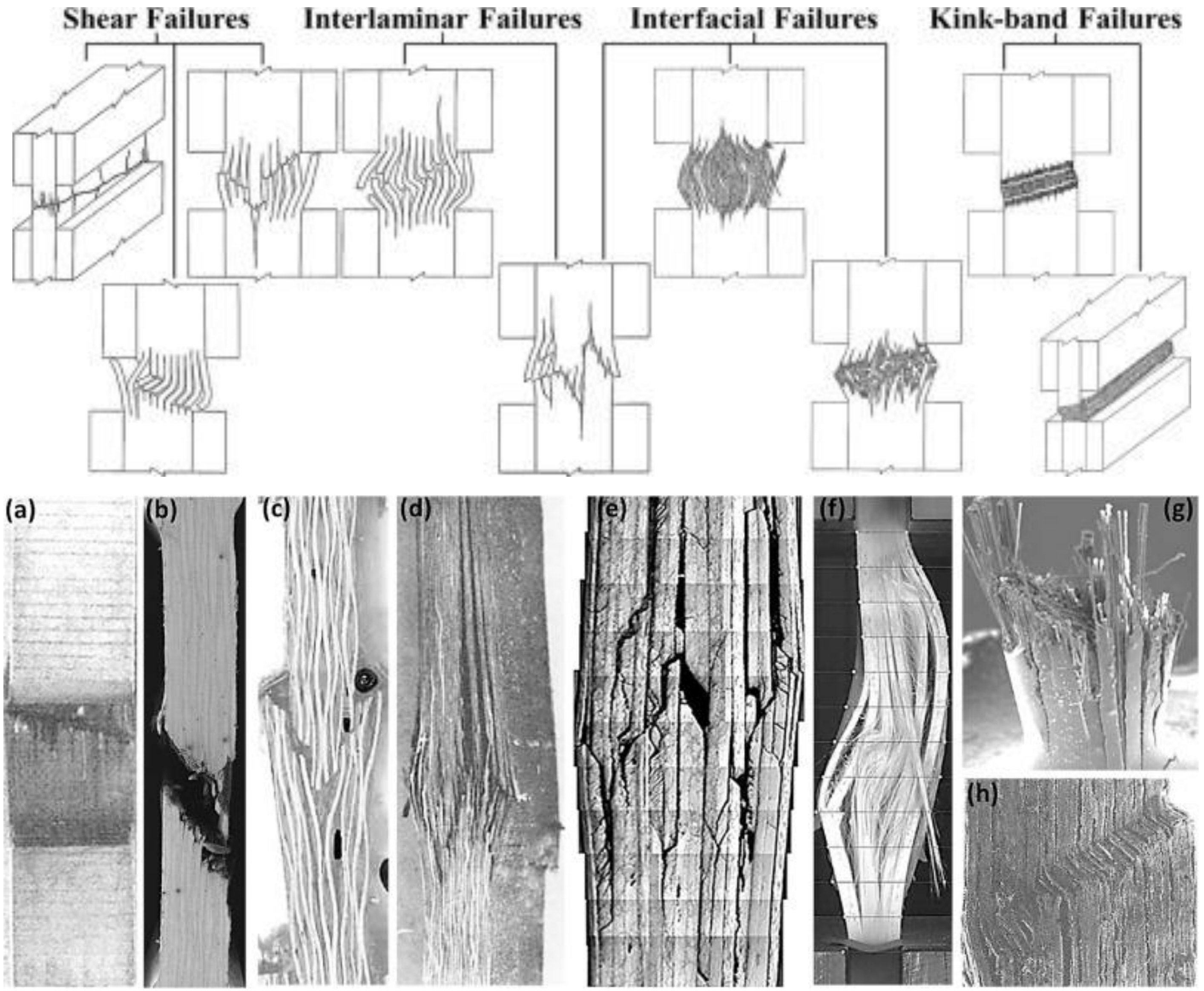
Combined loading methods: Test fixture for ASTM D 6641/D 6641M



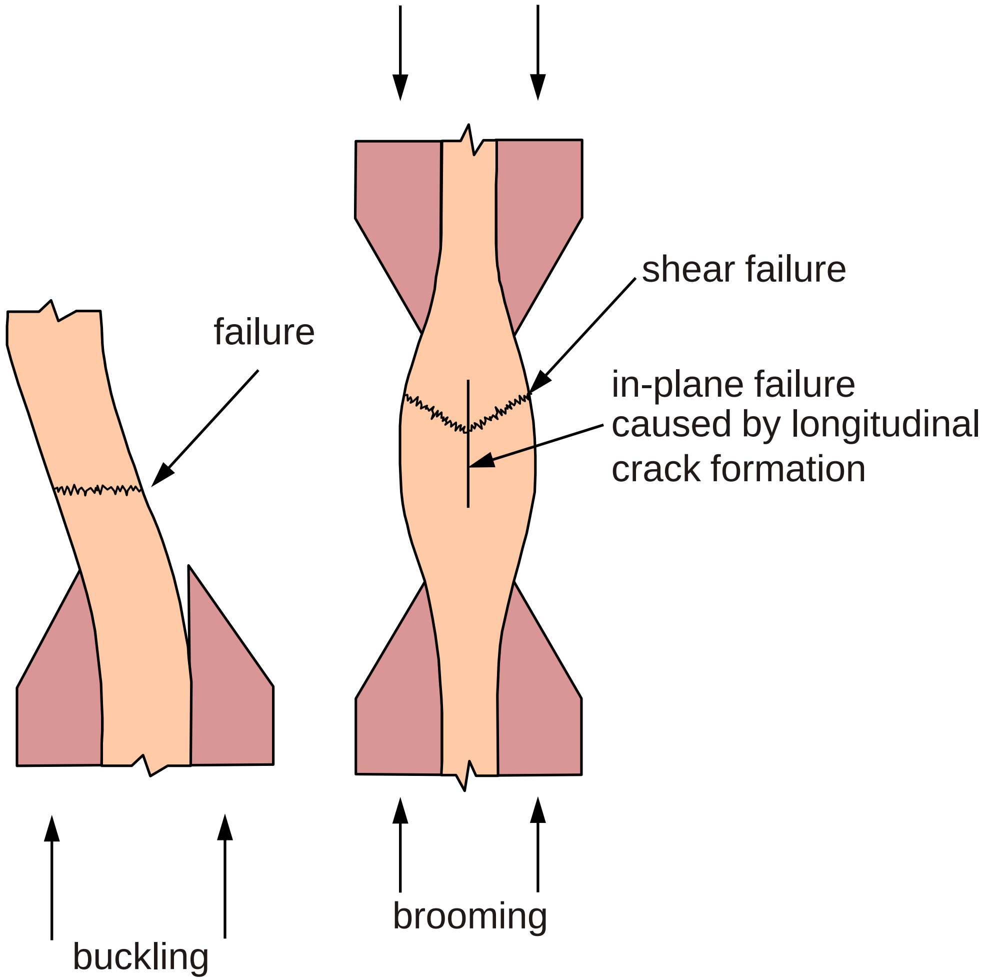


Compression test failures

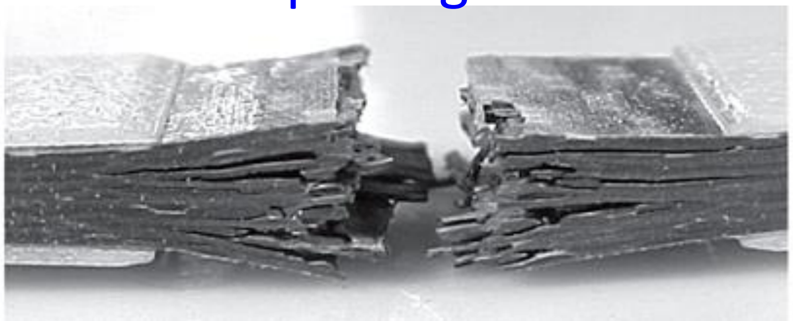
Examples of the failure modes:
(a) in-plane shear,
(b) through-the-thickness shear,
(c) wedge splitting,
(d) delamination buckling,
(e) longitudinal cracking,
(f) brooming,
(g) fiber crushing
(h) kink-band failure.



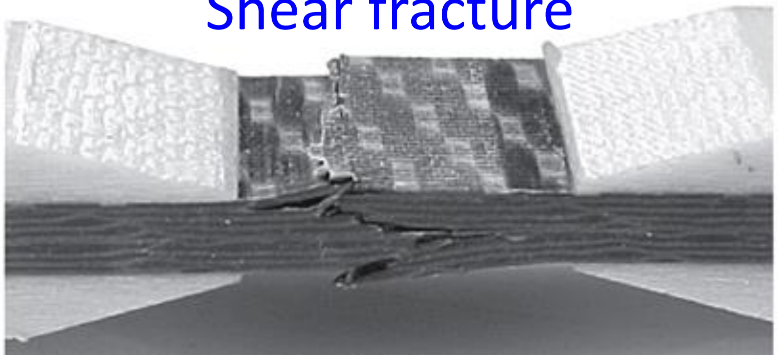
Compression test failures



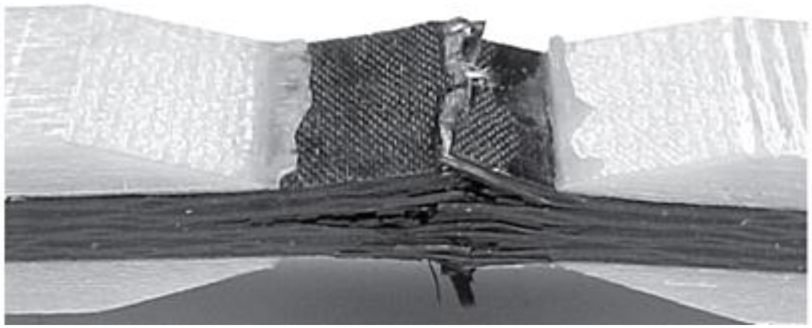
Axial splitting fracture



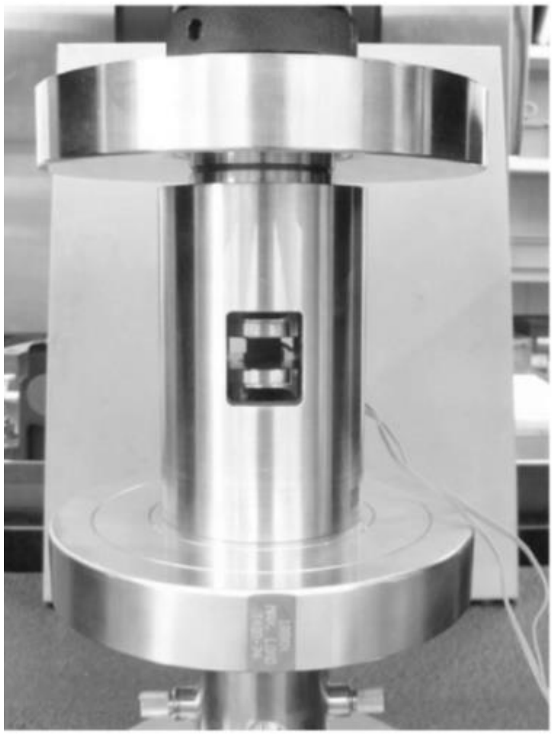
Shear fracture

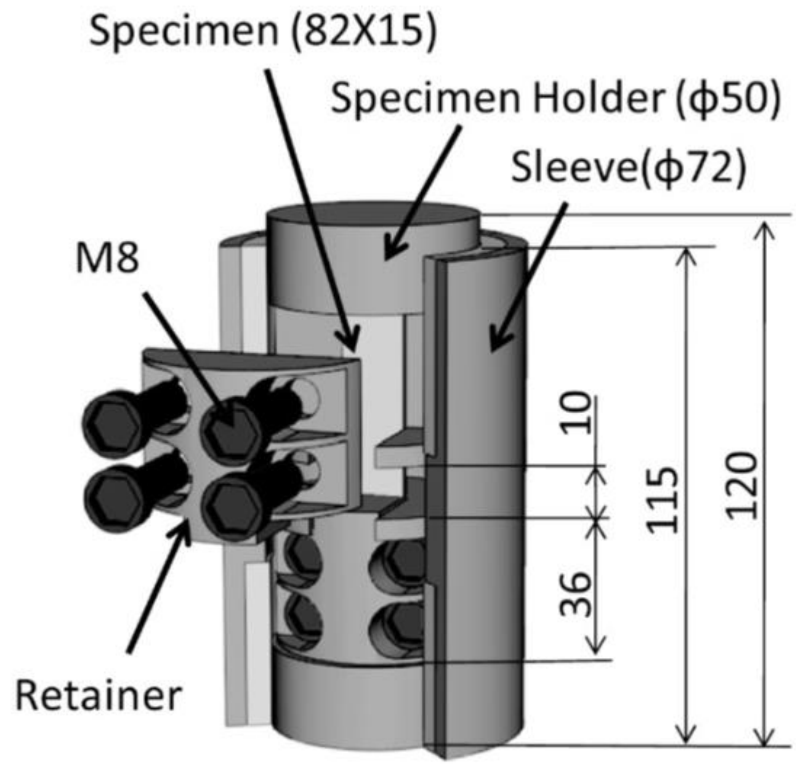


“Kink zones” fracture



Compression testing using NAL-II method (proposed by JAXA) - combined loading method



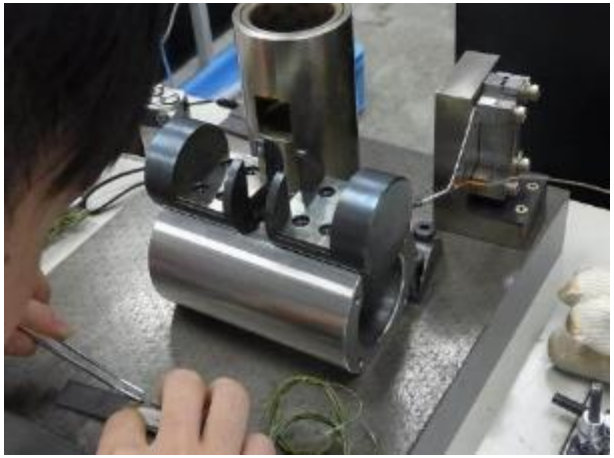


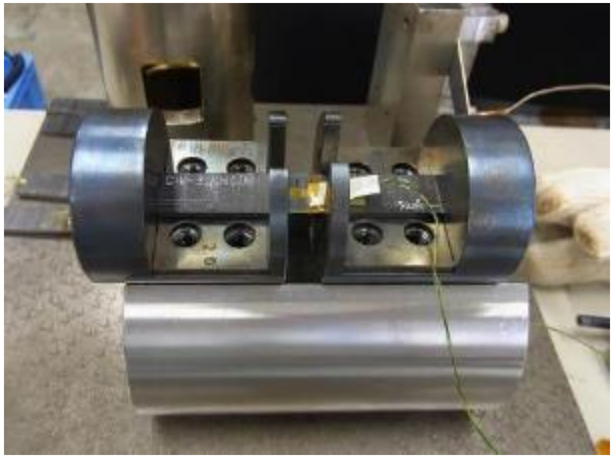
Test fixture for NAL-II compressive test method.

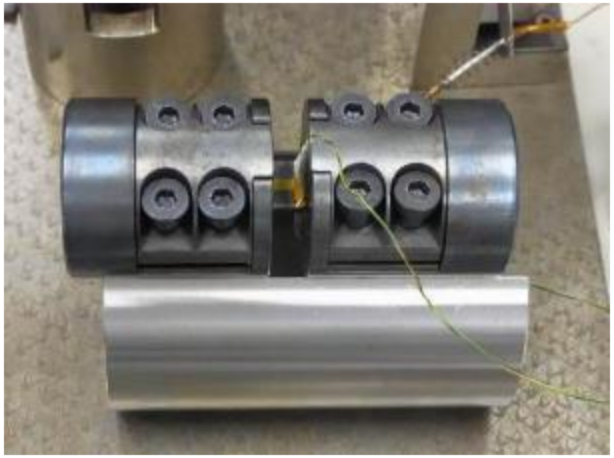
Ogasawara T, Ishikawa T. Proposal of a Convenient Compressive Test Method for Carbon Fiber Reinforced Plastics Composites. Journal of the Japan Society for Composite Materials, 36(2), 33-40, 2010.

6.3. Mechanical testing of lamina and laminate

Compression testing using NAL-II method (proposed by JAXA) - combined loading method



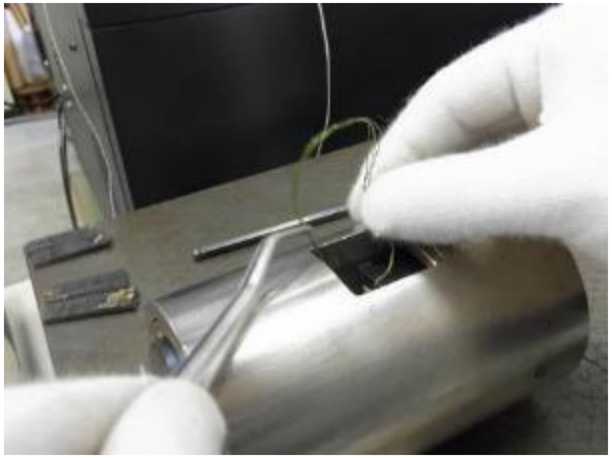


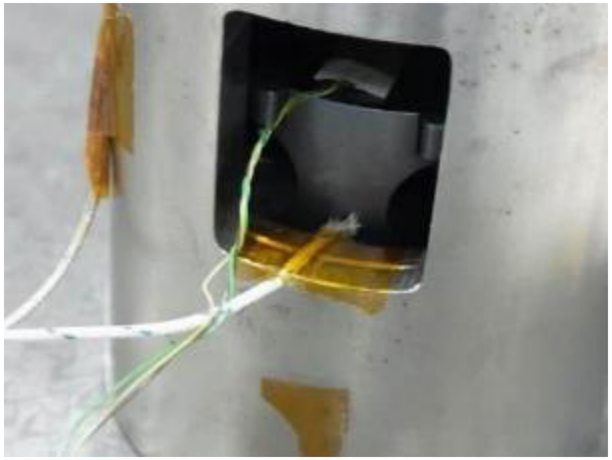
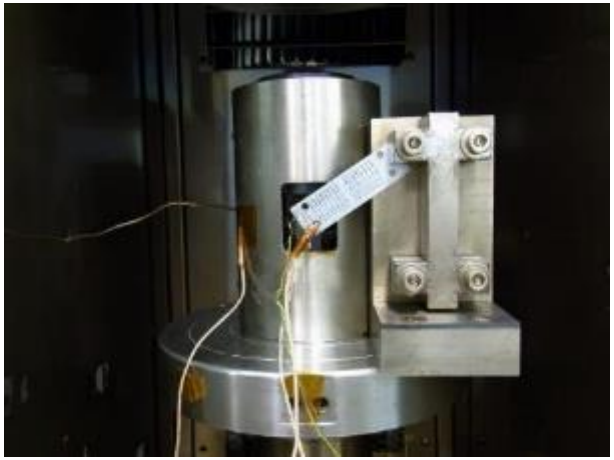


6.3. Mechanical testing of lamina and laminate

Compression testing using NAL-II method (proposed by JAXA) - combined loading method

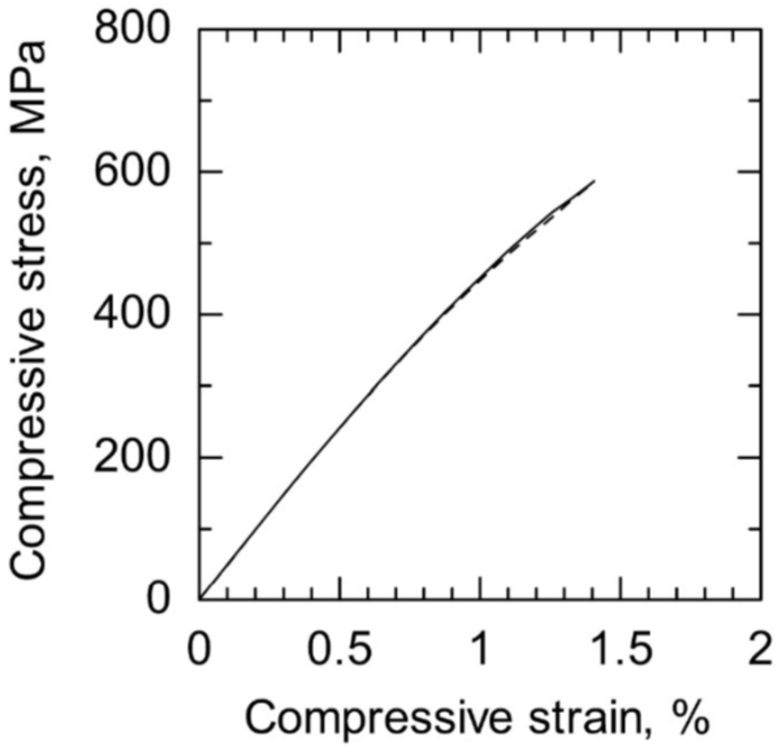




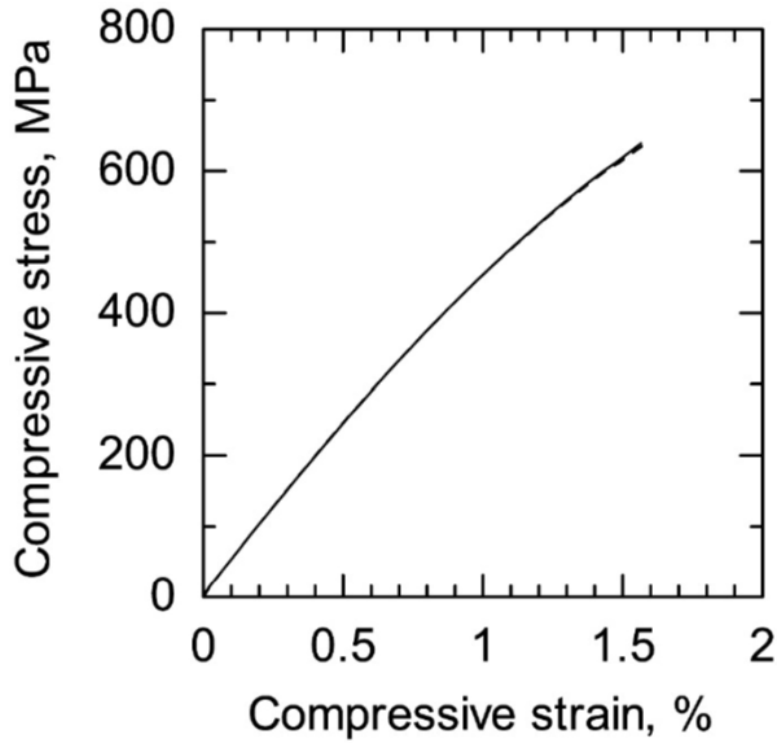



6.3. Mechanical testing of lamina and laminate

Compression testing using NAL-II method (proposed by JAXA) - combined loading method



Typical stress-strain curves of T800S/ 3900-2B (ASTM D6641).

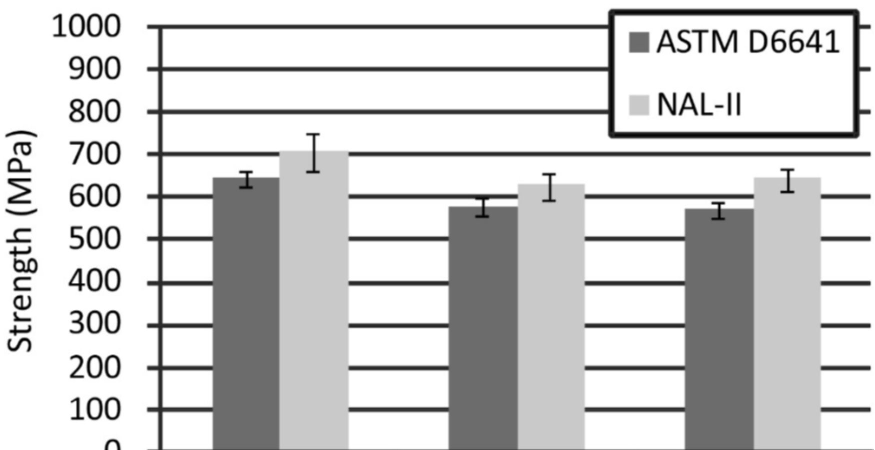


Typical stress-strain curves of T800S/ 3900-2B (NAL-II).

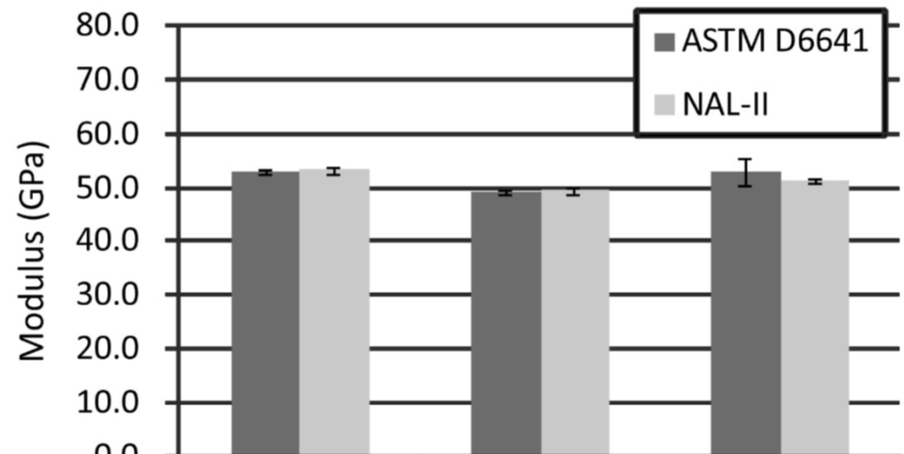
Ogasawara T, Ishikawa T. Proposal of a Convenient Compressive Test Method for Carbon Fiber Reinforced Plastics Composites. Journal of the Japan Society for Composite Materials, 36(2), 33-40, 2010.

6.3. Mechanical testing of lamina and laminate

Compression testing using NAL-II method (proposed by JAXA) - combined loading method



	T800/3633	T800S/3900-2B	IM600/133
ASTM D6641	644	578	571
NAL-II	705	626	643



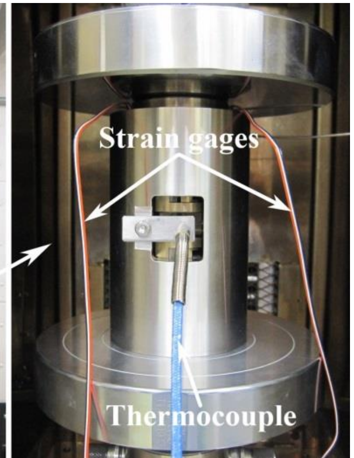
	T800/3633	T800S/3900-2B	IM600/133
ASTM D6641	53.0	49.2	53.0
NAL-II	53.2	49.5	51.4

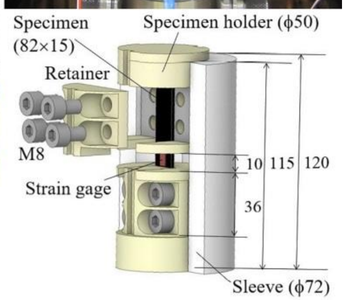
Average strengths obtained by ASTM D6641 and NAL-II compressive test methods (Error bar; standard deviation).

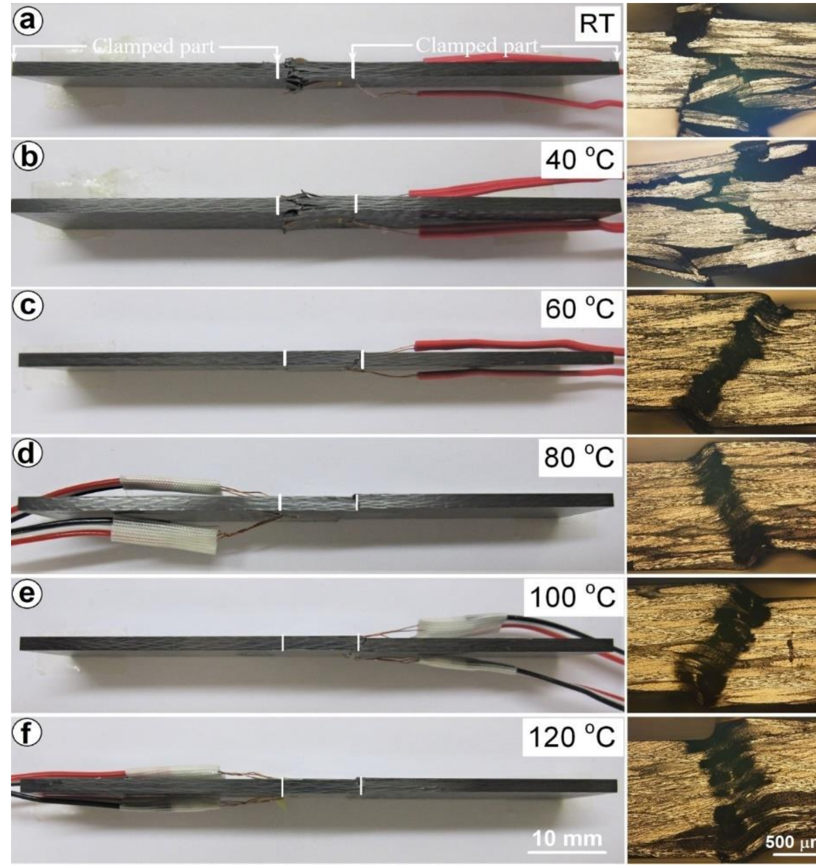
Ogasawara T, Ishikawa T. Proposal of a Convenient Compressive Test Method for Carbon Fiber Reinforced Plastics Composites. Journal of the Japan Society for Composite Materials, 36(2), 33-40, 2010.

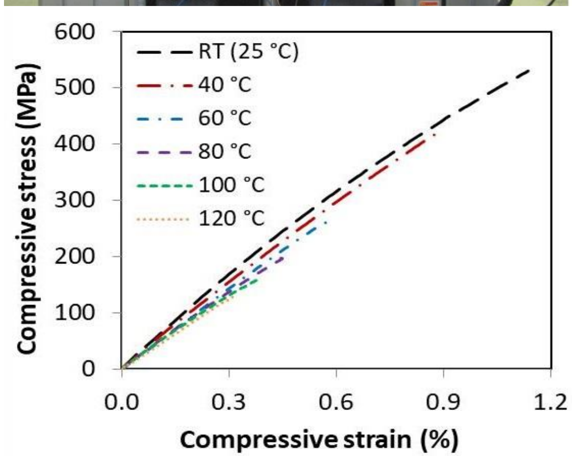
6.3. Mechanical testing of lamina and laminate

Compression testing using NAL-II method - combined loading method







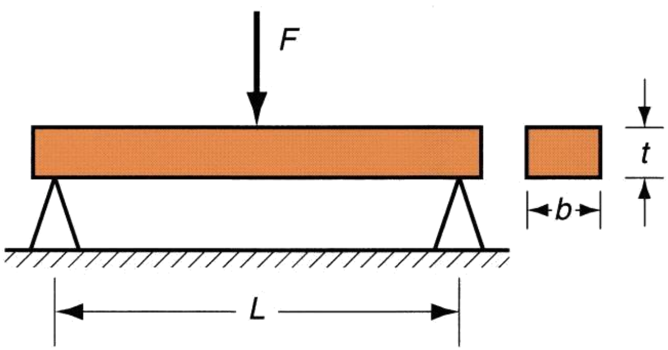


Tran Huu Nam, Ken Goto, et al. "Time-and temperature-dependent compressive behavior of woven carbon fabric reinforced polyamide composite laminate." Journal of Composite Materials 57(5): 929-940, 2023.

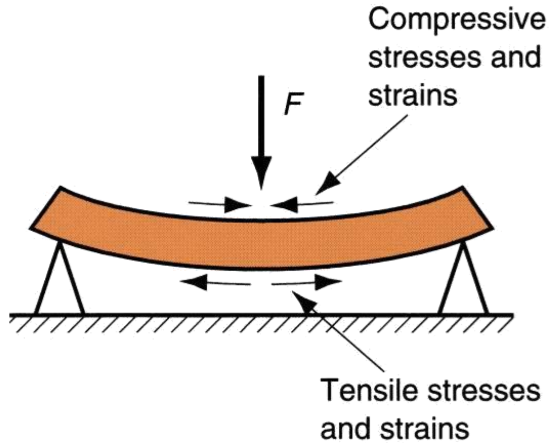
6.3. Mechanical testing of lamina and laminate

Bending (flexural) testing

Specimen of rectangular cross-section is positioned between two supports, and a load is applied at its center.



(1)



(2)

$$\sigma = \frac{Mz}{I}$$

$$z = \frac{t}{2},\; I = \frac{1}{12}bt^3, M = \frac{FL}{4}$$

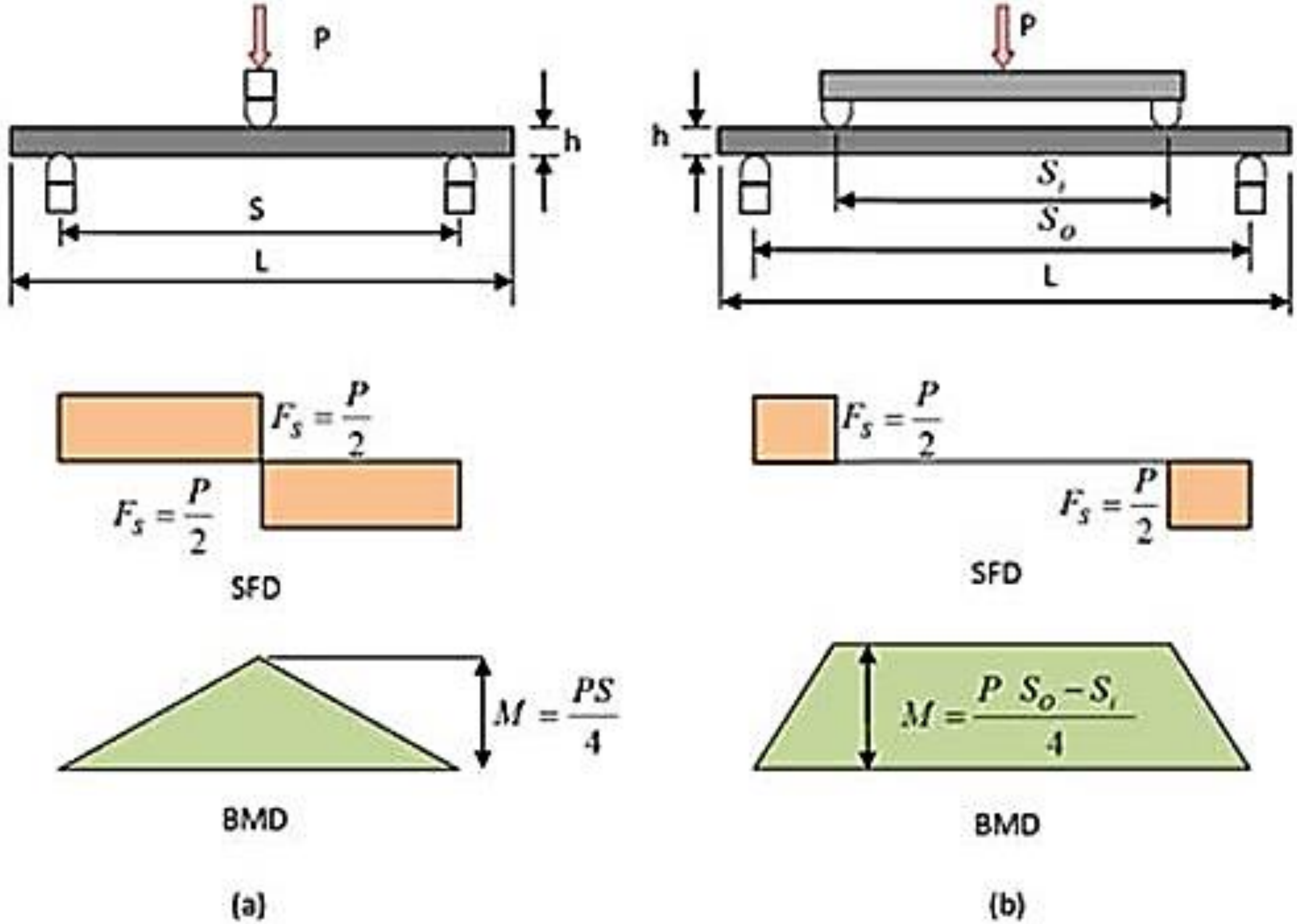
$$\sigma = \frac{Mz}{I} = \frac{\frac{FL}{4}\cdot\frac{t}{2}}{\frac{1}{12}bt^3} = \frac{3FL}{2bt^2}$$

Bending of a rectangular cross-section results in both tensile and compressive stresses in the material: (1) initial loading; (2) highly stressed and strained specimen.

Bending (flexural) testing

3-point and 4-point bending tests:

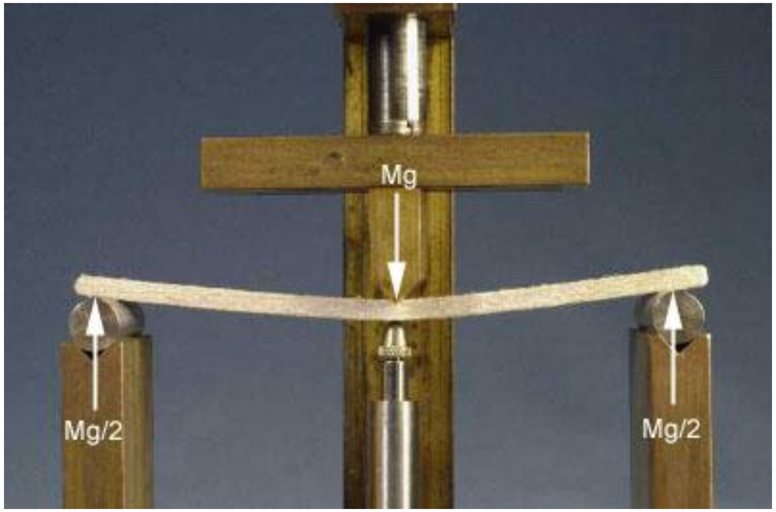
Shear force and bending moment diagrams for (a) three point and (b) four point bending test

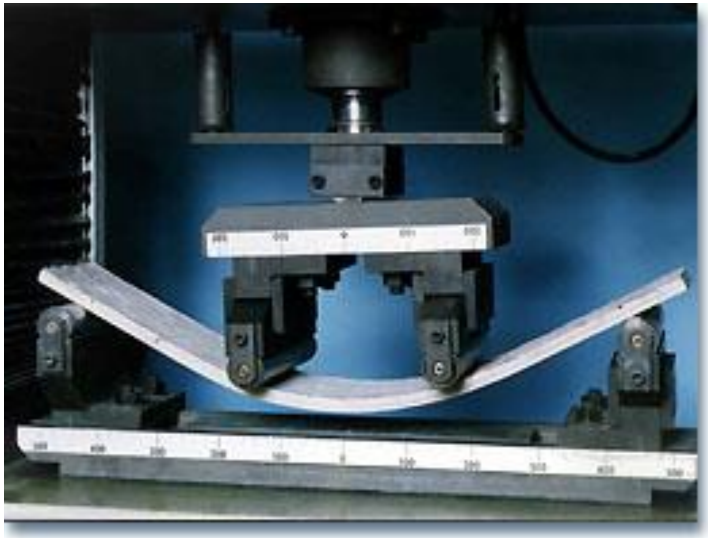


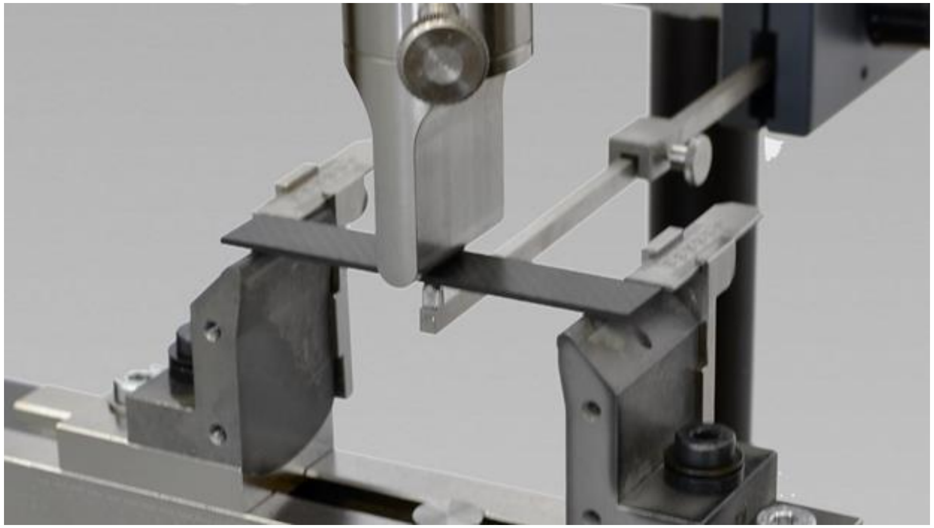
6.3. Mechanical testing of lamina and laminate

Bending (flexural) testing

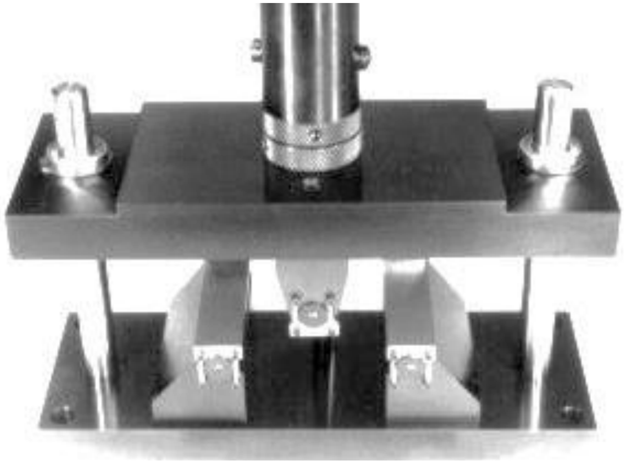
3-point and 4-point bending tests:

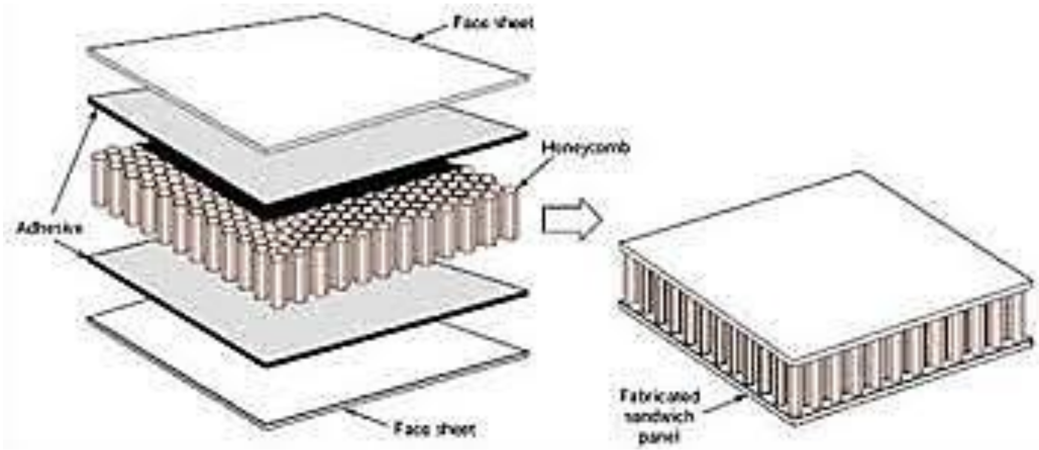


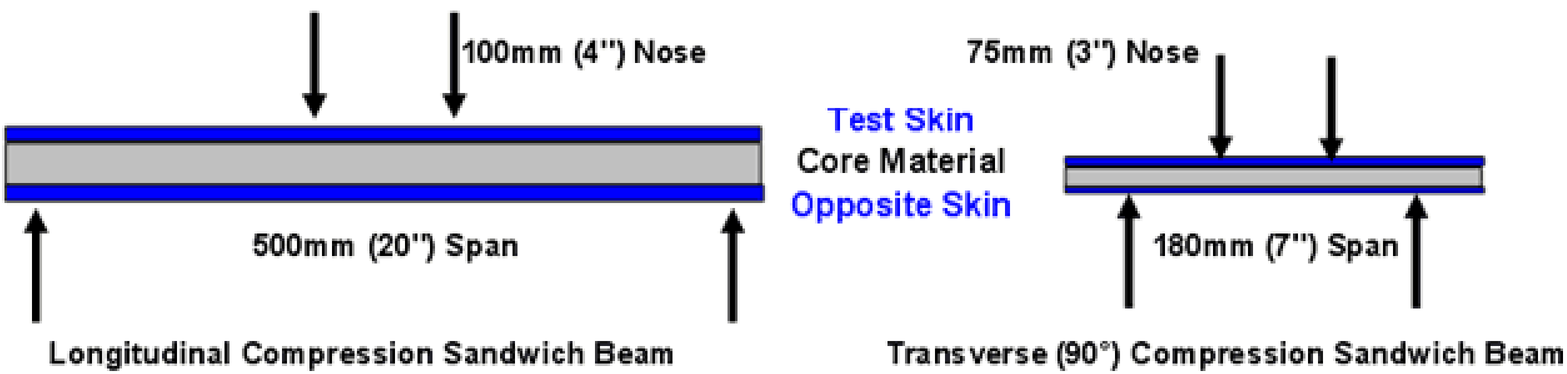




Bending (flexural) testing for Sandwich Beam – ASTM D 5467



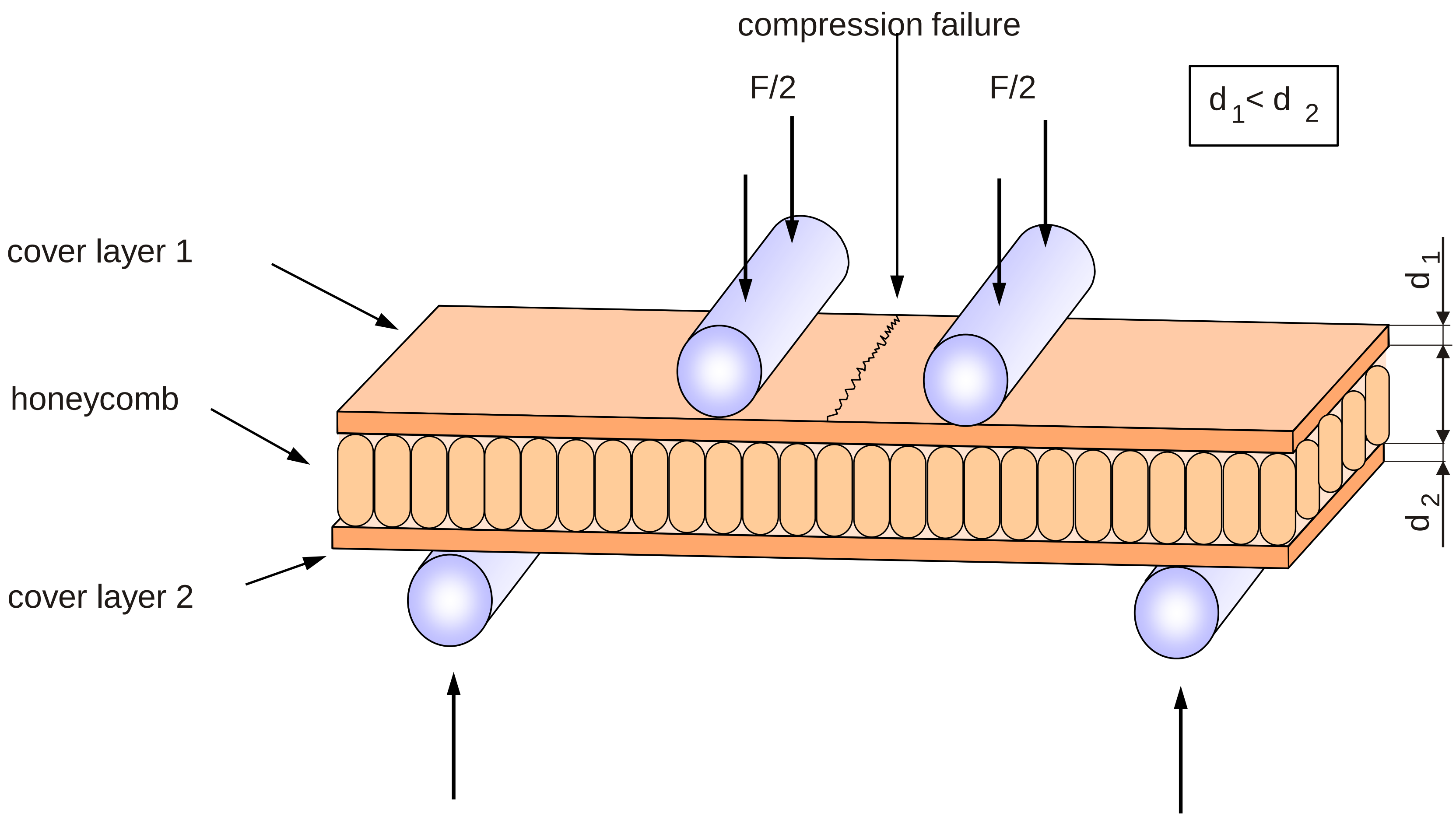




Advantages: Simple fixture; reliable results with proper specimen (core) design
Disadvantages: Large specimens (materials expense); failure must occur in compressive face sheet

Bending (flexural) testing for Sandwich Beam – ASTM D 5467

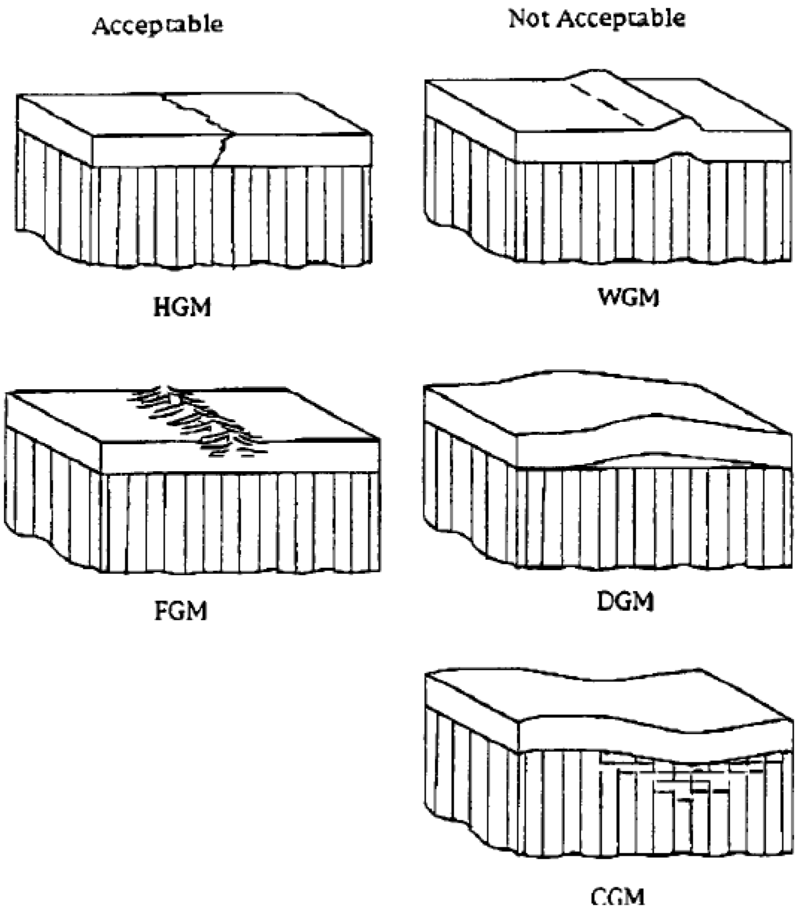
Load application by four-point bending



Bending (flexural) testing for Sandwich Beam – ASTM D 5467

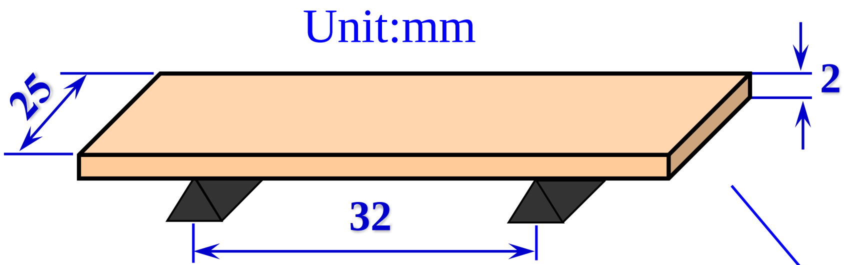
Failure Code

Type	Code	Area	Code	Location	Code
Skin to core Delamination	D	At load cylinder	A	Left	L
Filament fracture	F	Gage	G	Right	R
tHrough–thickness	H	Multiple areas	M	Middle	M
Layer instability	L	Outside gage	U	Various	V
local Wrinkling	W	Various	V	Unknown	U
Multi–mode	M L	Unknown	U		
core Crushing	C				
long.–Splitting	S				
Transverse shear	T				
eXplosive	X				
Other	O				



6.3. Mechanical testing of lamina and laminate

Flexural specimen



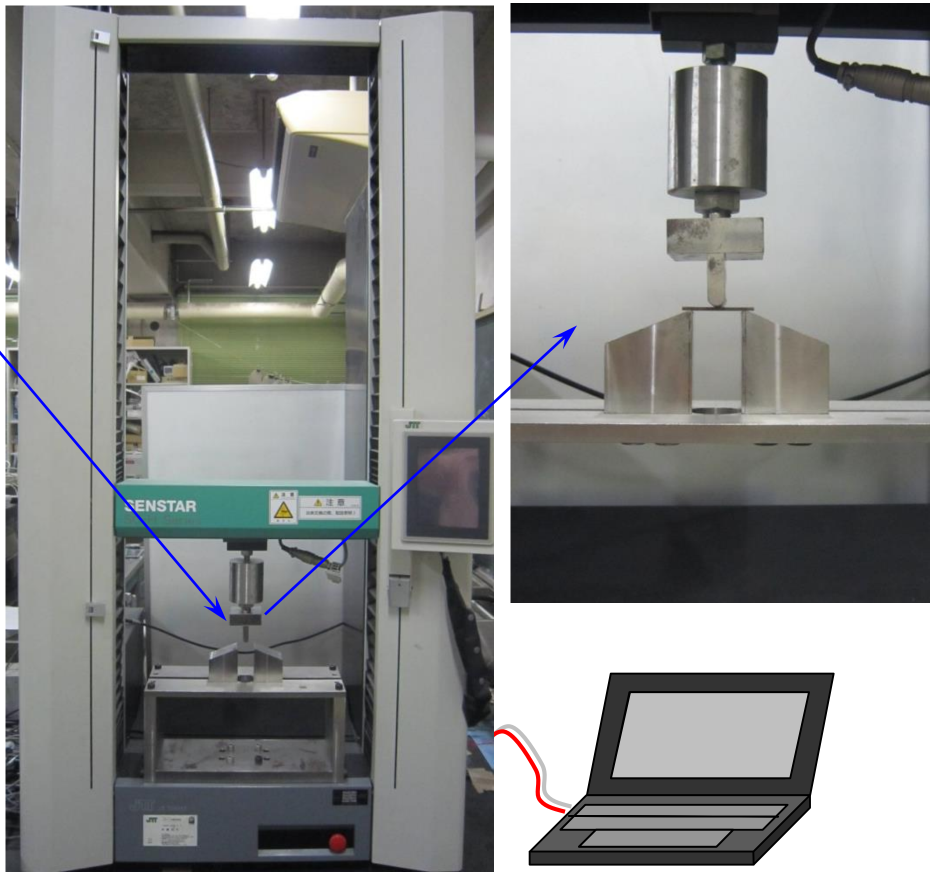
Specimen length: 50 mm
Span length (L_s): 32 mm
Crosshead speed : 2 mm/min

The flexural strength (σ_f) and modulus (E_f) were calculated using the following equations:

$$\sigma_f = \frac{3FL_s}{2bh^2} \qquad E_f = \frac{L_s^3 m}{4bh^3}$$

m is the slope of the force-deflection curve

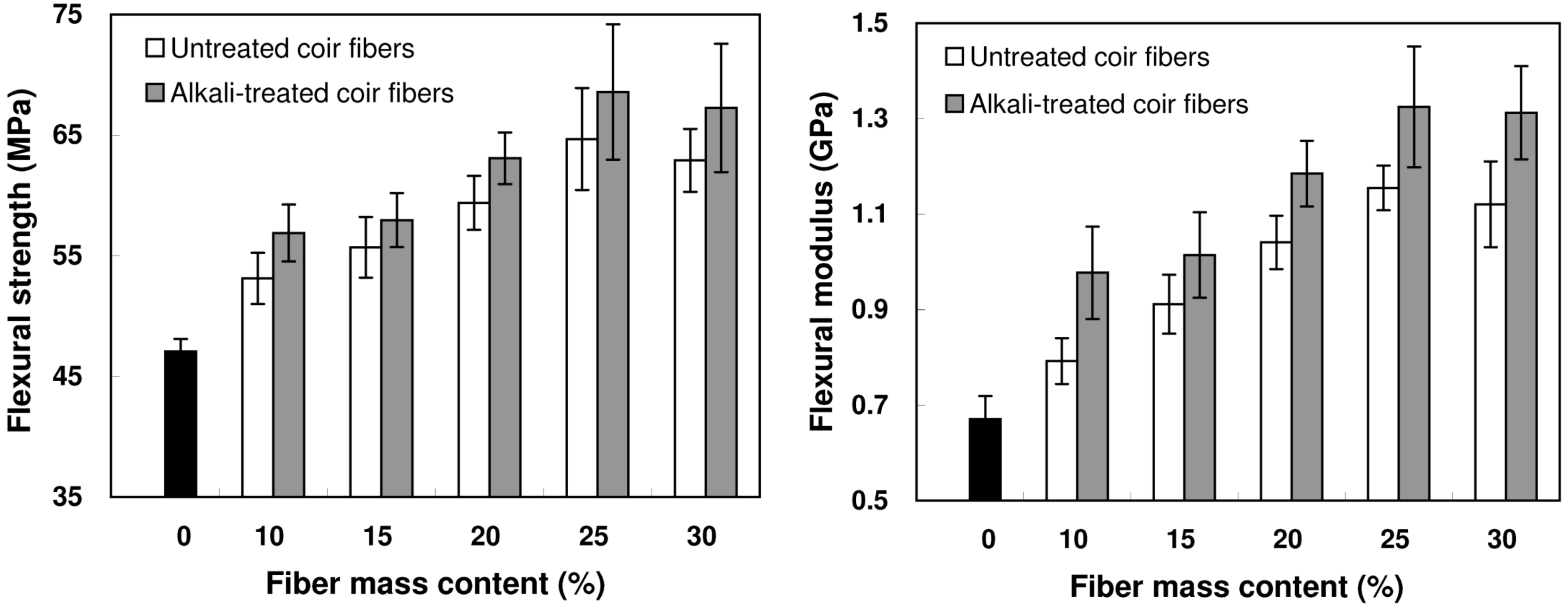
Universal testing machine



SENSTAR SC-5H (5000N)

Tran Huu Nam et al., Effect of alkali treatment on interfacial and mechanical properties of coir fiber reinforced poly(butylene succinate) biodegradable composites. *Composites Part B: Engineering*, vol. 42(6), 1648-1656, 2011.

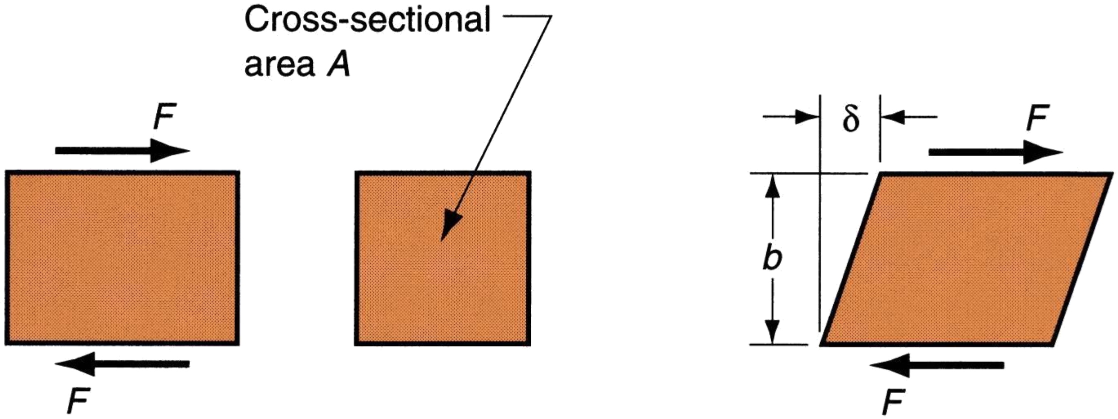
Flexural Properties of Coir fiber reinforced PBS composites



The best flexural properties can be obtained at fiber mass content of 25% corresponding with the tensile properties. The mechanical strength and modulus of coir/PBS biodegradable composites showed that the optimum fiber mass content is 25%.

Tran Huu Nam et al., *Composites Part B: Engineering*, Vol. 42(6), pp. 1648-1656, 2011

Shear test Application of stresses in opposite directions on either side of a thin element



Shear stress (or tau) defined as $\tau = \dfrac{F}{A}$

where F = applied force; and A = area over which deflection occurs.

Shear strain (or gamma) defined as $\gamma = \dfrac{\delta}{b}$

where δ = delta or amount of deflection; and b = distance over which deflection occurs

Shear test

In the elastic region, the relationship is defined as

$$\tau = G\gamma$$

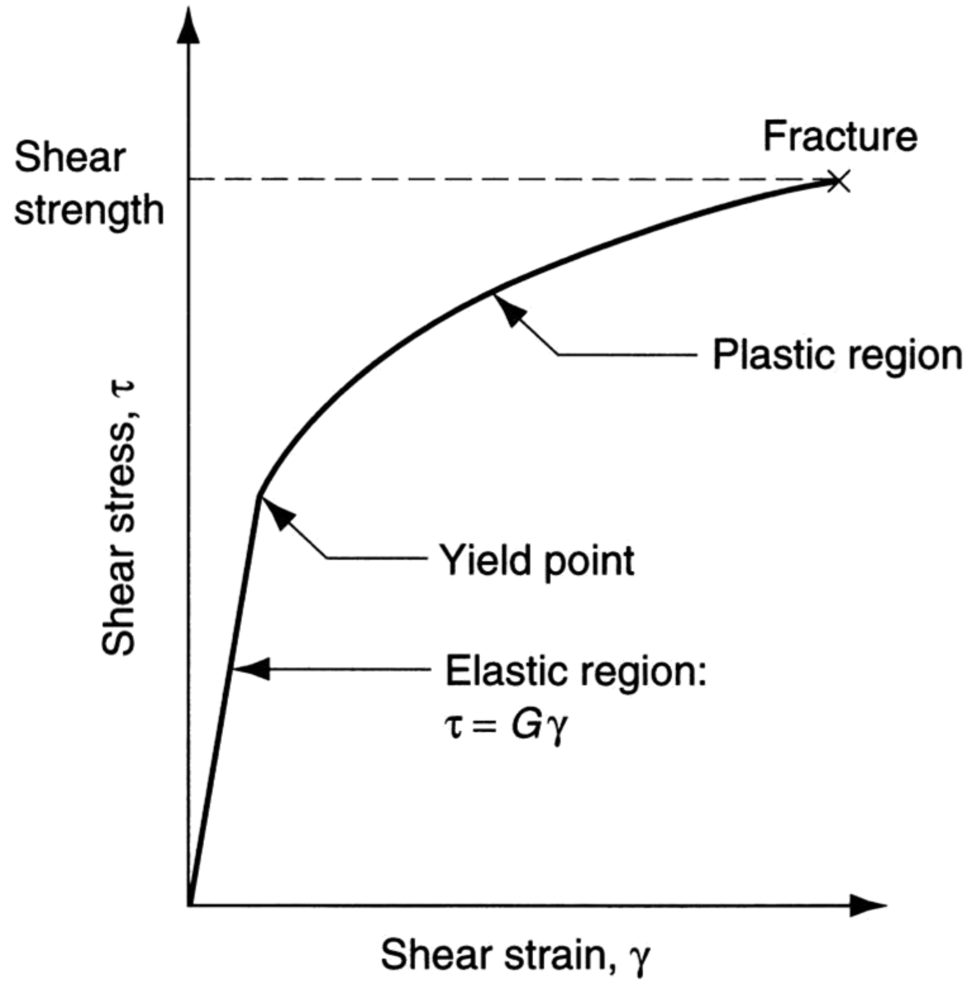
where G = *shear modulus*, or *shear modulus of elasticity*

For most materials,

$$G \approx 0.4E$$

where E = elastic modulus

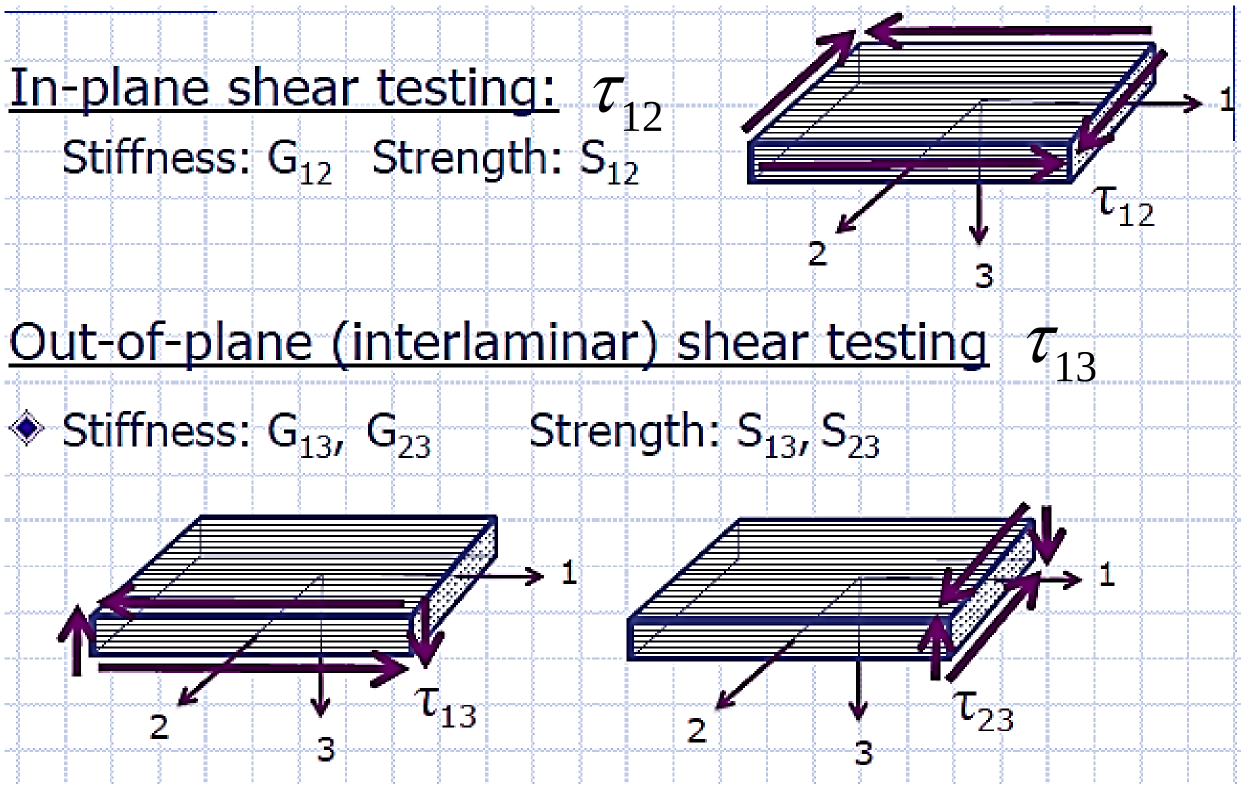
Shear Stress-Strain Curve



Typical shear stress-strain curve from a shear test.

Shear test of composites

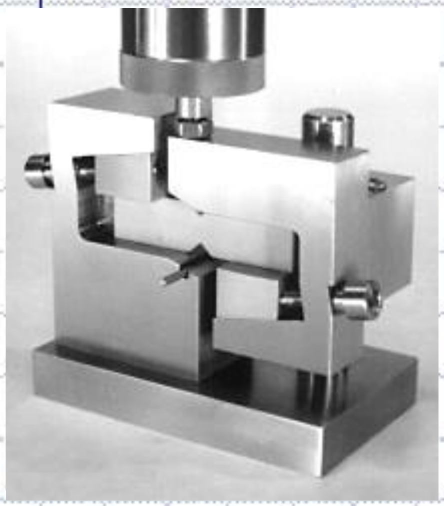
The measurement of shear properties in composites is a very difficult and challenging task. Some of the methods used to measure the shear moduli G_{12}, G_{13}, G_{23} are following

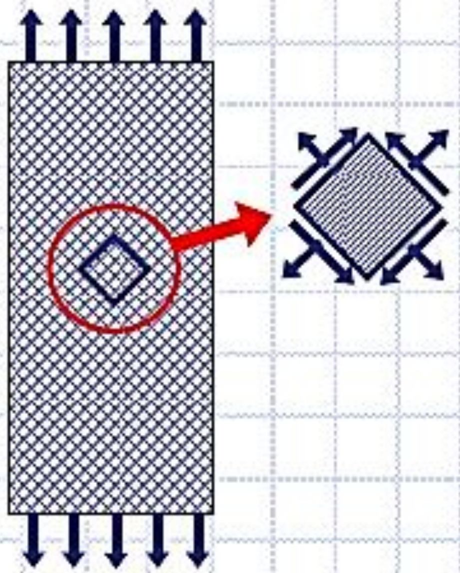


6.3. Mechanical testing of lamina and laminate

Shear test of composites

Common Test Methods: In-Plane Shear





Iosipescu Shear

ASTM D 5379

- 3 x 0.75 in. specimen
- Edge loaded

V-Notched Rail Shear

ASTM D 7078

- 3 x 2.2 in. specimen
- Face loaded
- Recommended by CMH-17

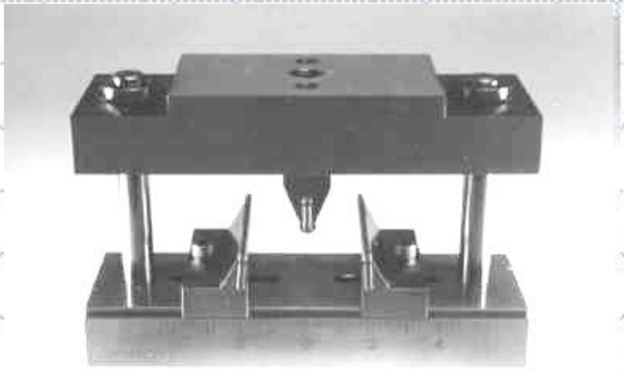
±45 Tension Shear

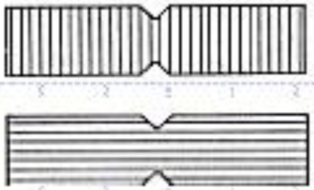
ASTM D 3518

- Combined stress state (not pure shear)
- Easy to perform

Shear test of composites

Common Test Methods: Out-Of-Plane (Interlaminar) Shear





Short Beam Shear

ASTM D 2344

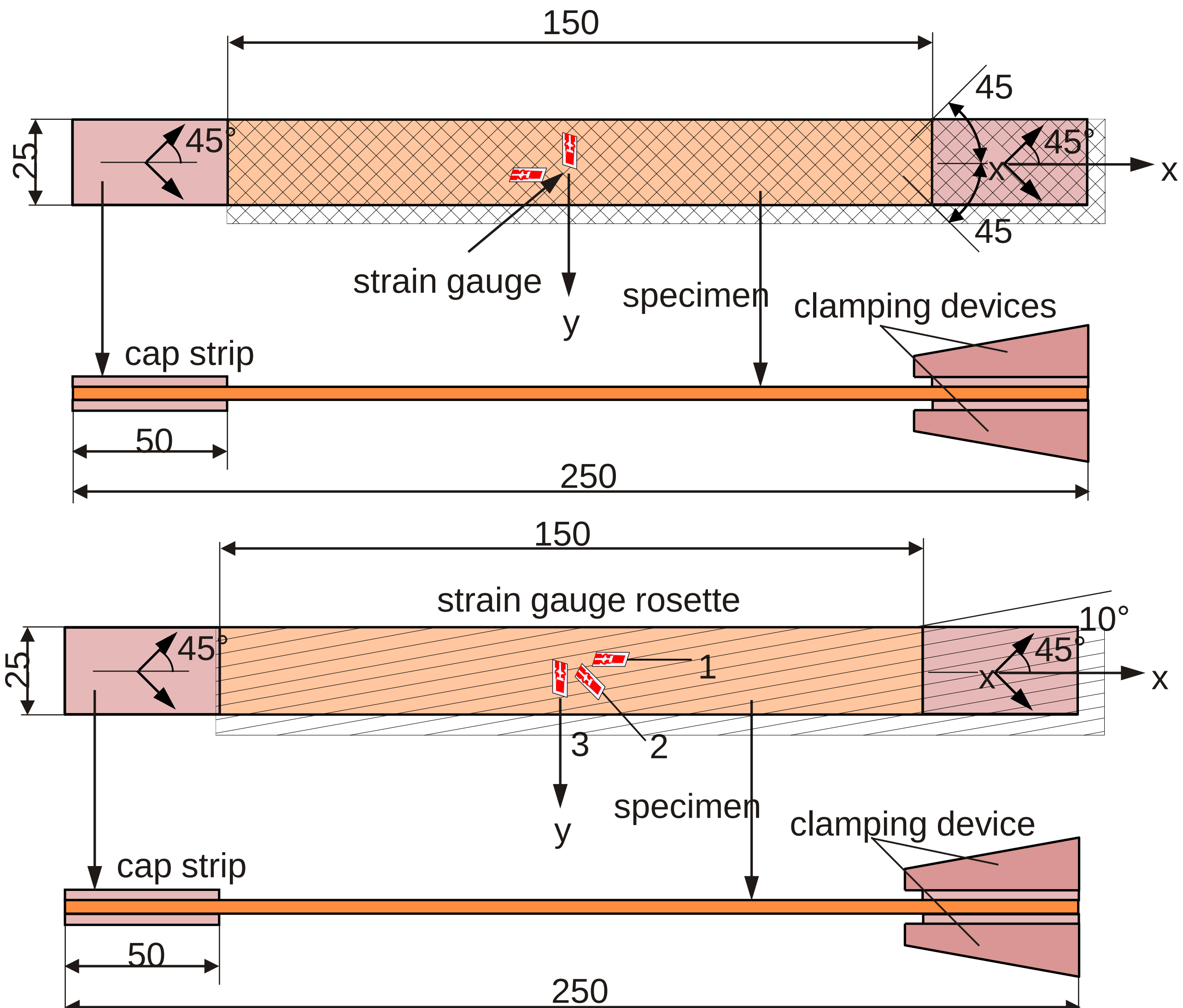
- Shear strength only
- Combined stress state
- Small specimen
- Simple and affordable test

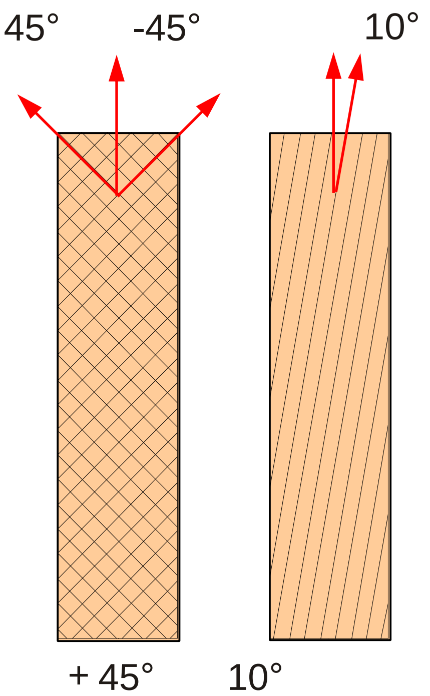
Iosipescu Shear

ASTM D 5379

- 3 x 0.75 in. specimen
- Edge loaded
- Modulus and strength

Shear test of composites: ±45 tensile shear test - ASTM D3518





Shear test of composites: ±45 tensile shear test - ASTM D3518

Shear stress from applied stress:

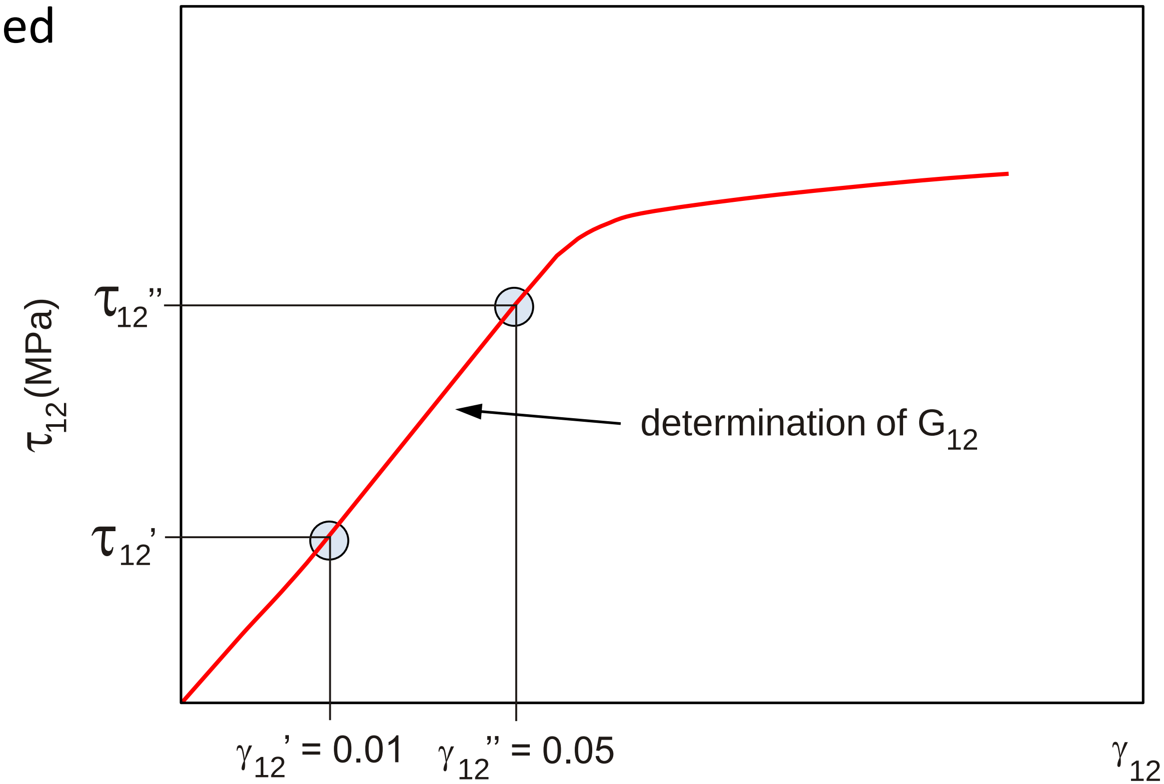
$$\tau_{12} = \frac{\sigma_x}{2}$$

Shear strain from measured normal strains:

$$\gamma_{12} = \varepsilon_x - \varepsilon_y$$

Shear modulus:

$$G_{12} = \frac{\Delta\tau}{\Delta\gamma} = \frac{\tau''_{12} - \tau'_{12}}{\gamma''_{12} - \gamma'_{12}}$$

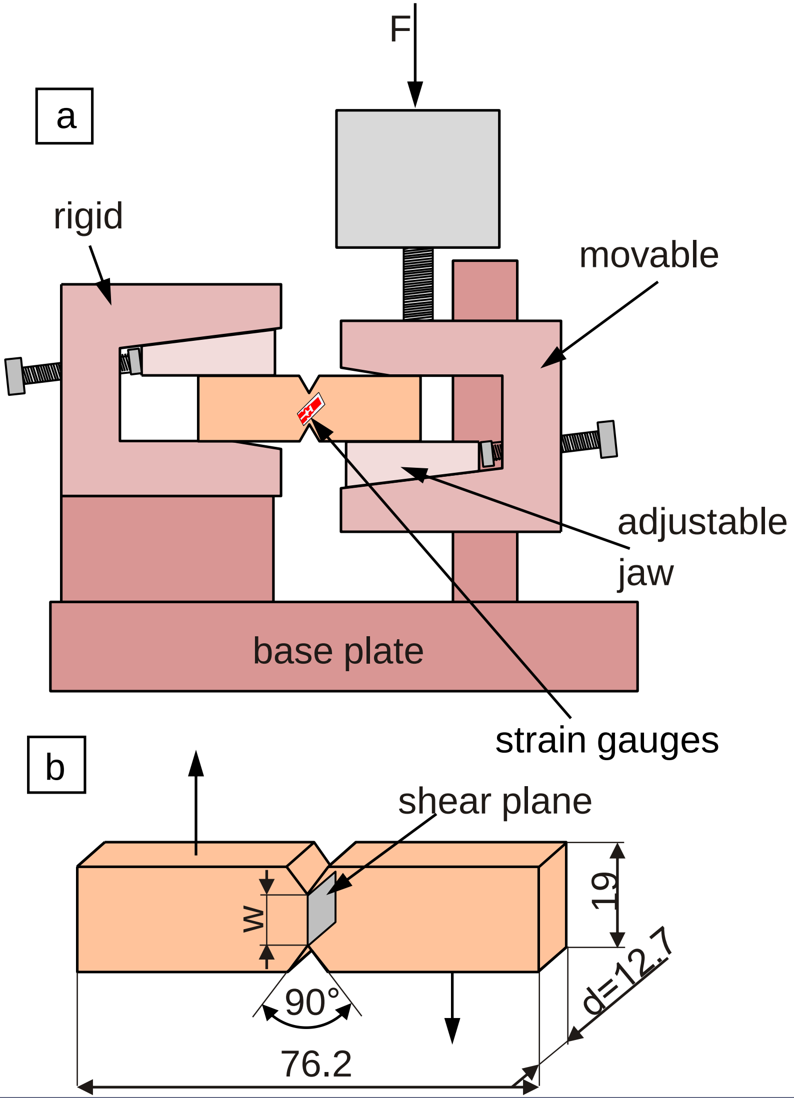


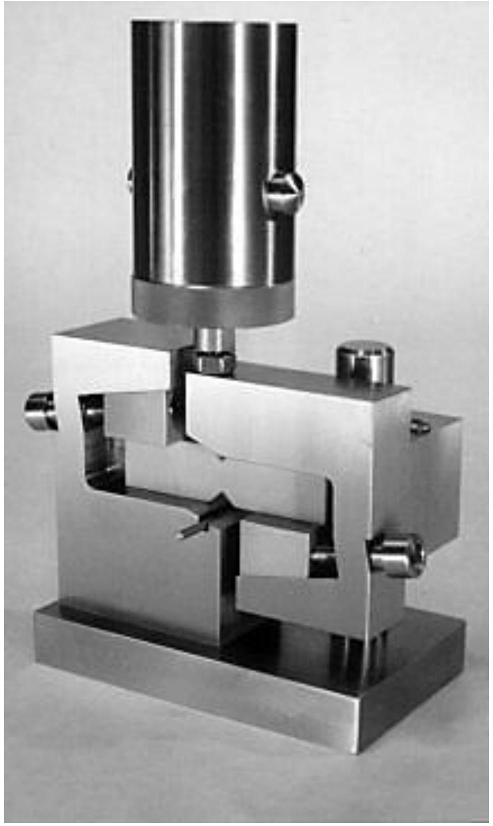
Advantages: Simple; uniform stress state; no fixture; damage growth representative of laminates
Disadvantages: Tabbing; alignment; strength dependent on layup; scissoring; t_{12} and t_{13} failure; edge delamination; s-concentration due to tabs

Shear test of composites: Iosipescu Shear Test ASTM D5379

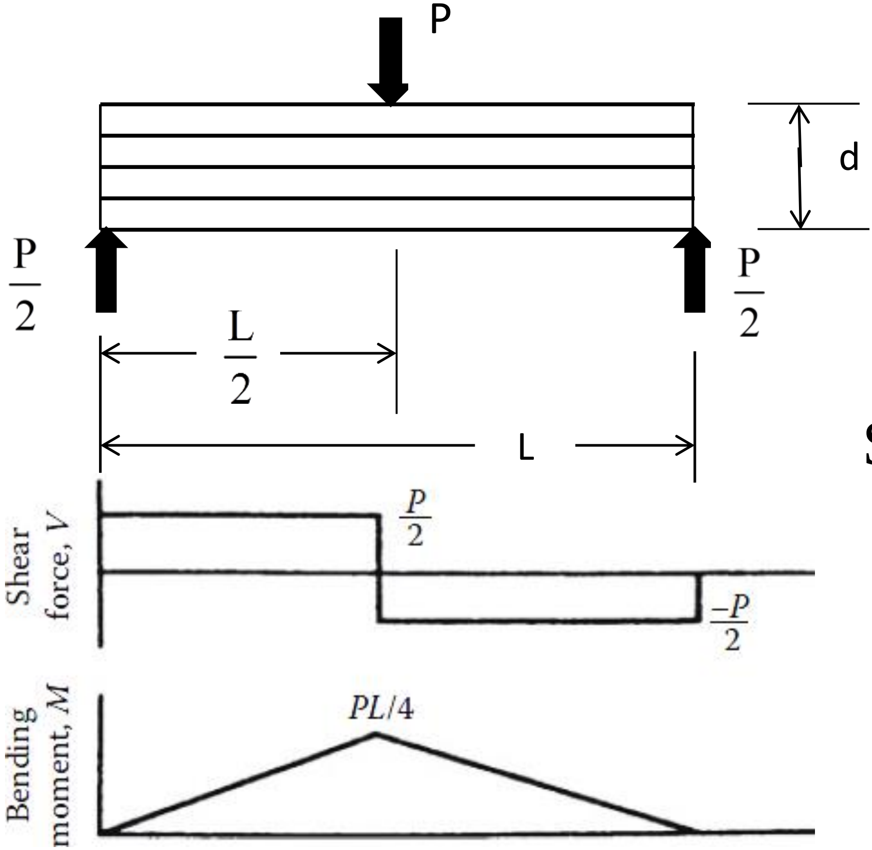
$$\tau_{12} = \frac{P}{dw}$$

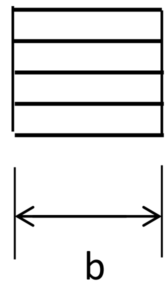
$$\gamma_{12} = \left|\varepsilon_{-45}\right| + \left|\varepsilon_{+45}\right|$$





Shear test of composites: Short Beam Shear ASTM D2344

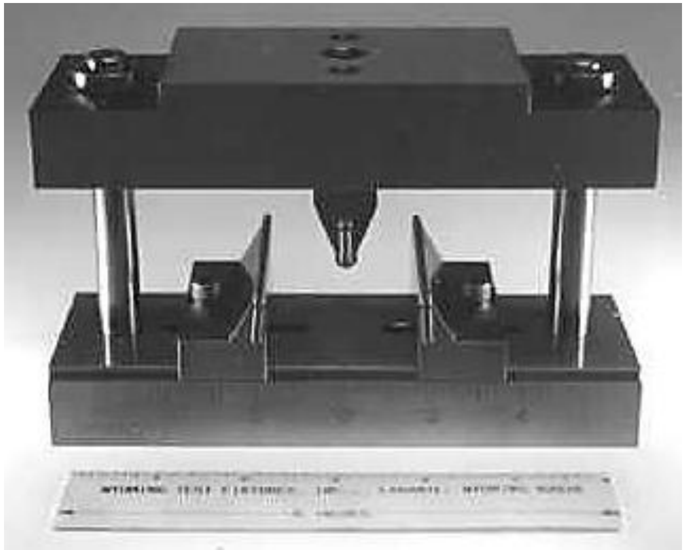




Shear stress

$$\tau_{xy} = \frac{VQ}{Ib}$$

$$\sigma_x = \frac{Mz}{I_{yy}}$$

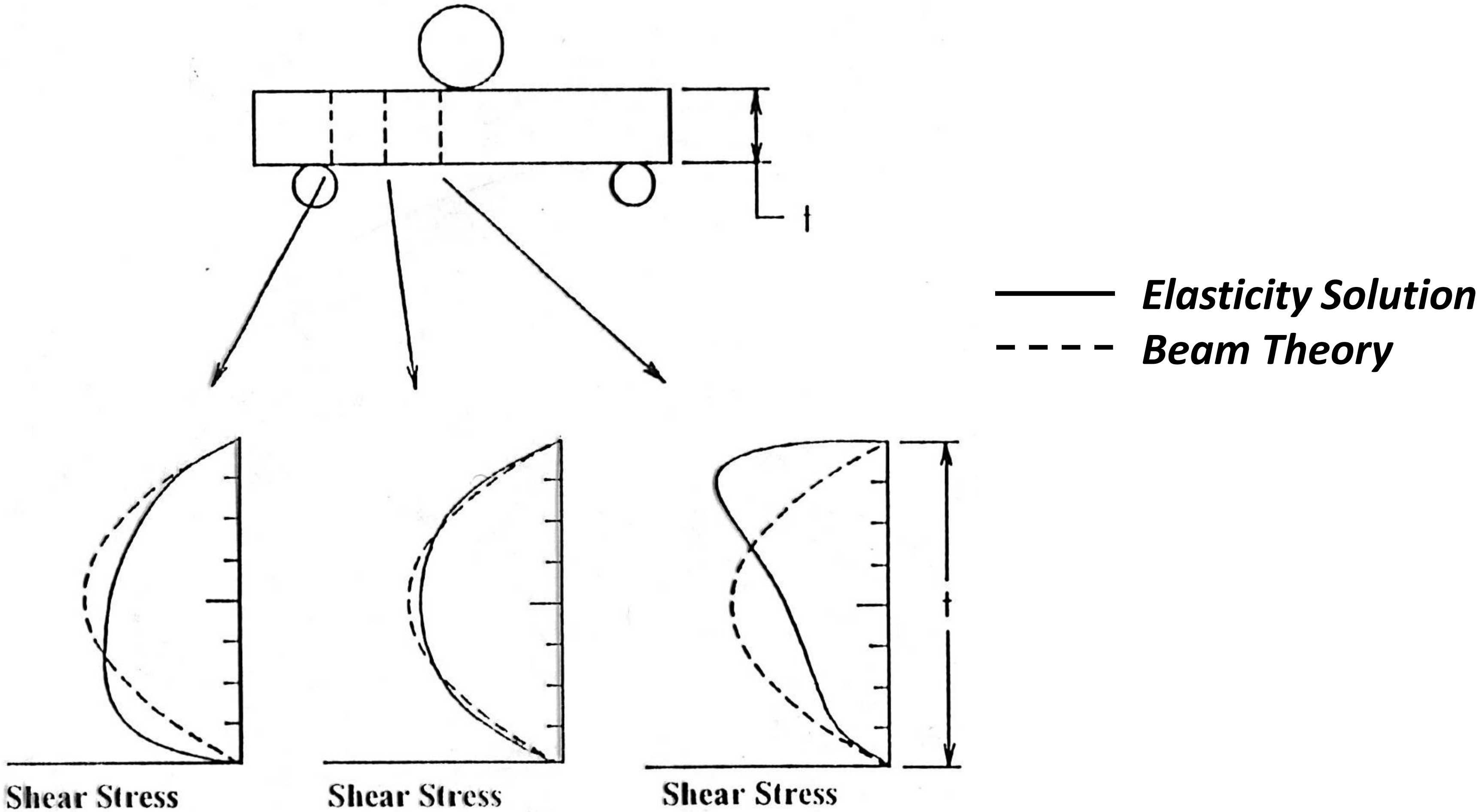


Note: not recommended for measurement of intrinsic properties, only for quality control and specification

Advantages: Simple test and fixture; small specimen

Disadvantages: Load introduction; no strain measurement; no modulus measurement; improper assumption of parabolic stress distribution; mixed mode failure

Shear test of composites: Short Beam Shear ASTM D2344

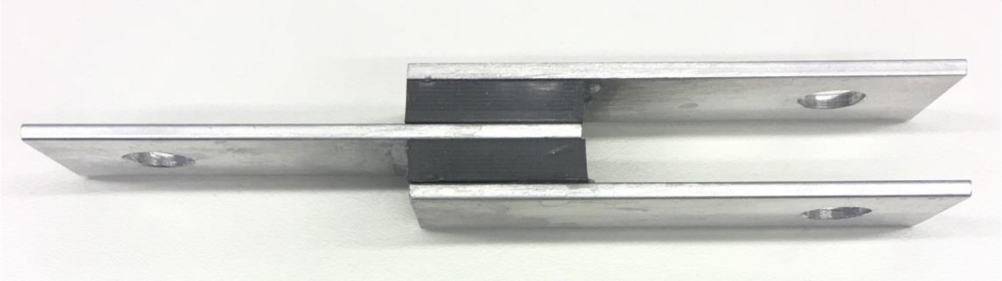


Stress Distribution in a Short Beam Shear Specimen

Double-lap shear test of magneto-sensitive elastomer composite (MEC)

Matrix	Liquid Silicone ZA13 and its catalyst (Havel Composites)
Reinforcement (70 wt.%)	Micro-sized Carbonyl Iron Particles (CIPs) (Sigma–Aldrich)

Specimen for Dynamic Double-lap Shear Tests	
Specimen Shape	Rectangular
Sample Dimensions	20 x 20 x 5 mm^3

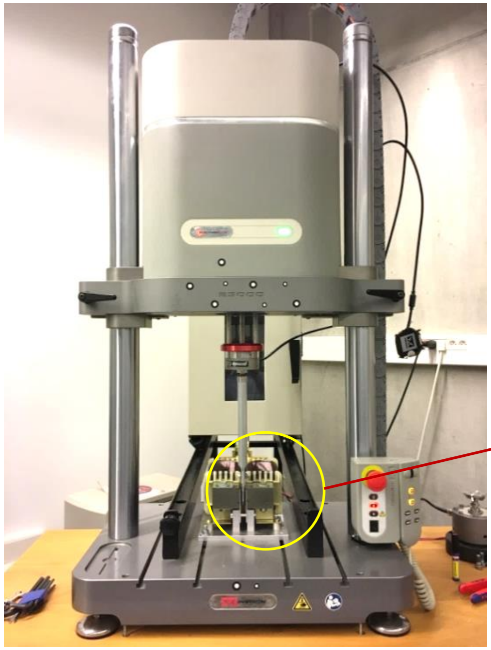


MEC specimen for dynamic double-lap shear test

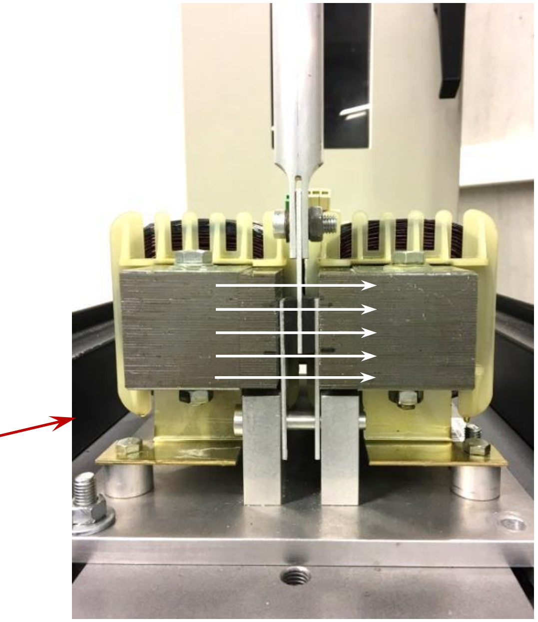
Tran Huu Nam, Iva Petríková, and Bohdana Marvalová. "Experimental characterization and viscoelastic modeling of isotropic and anisotropic magnetorheological elastomers". Polymer testing, vol. 81, 106272, 2020.

Double-lap shear test of magneto-sensitive elastomer composite (MEC)

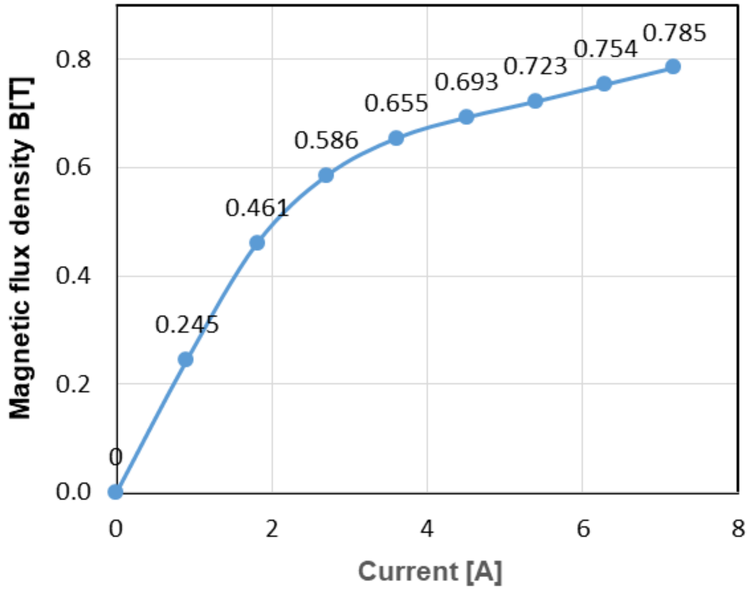
- The double-lap shear test for MEC specimens was conducted using Instron Electropuls testing system under harmonic loading in the displacement control mode.
- The amplitude of the cyclic shear strain was 0.1 and the frequency was changed in steps from 2 to 20 Hz.
- The samples were cyclically loaded under the magnetic field with the magnetic flux density increasing from 0 T to about 0.785 T.



Instron-Electropuls 3kN testing machine



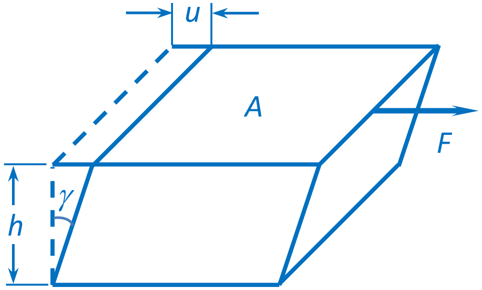
Horseshoe electromagnet with double-lap shear specimen



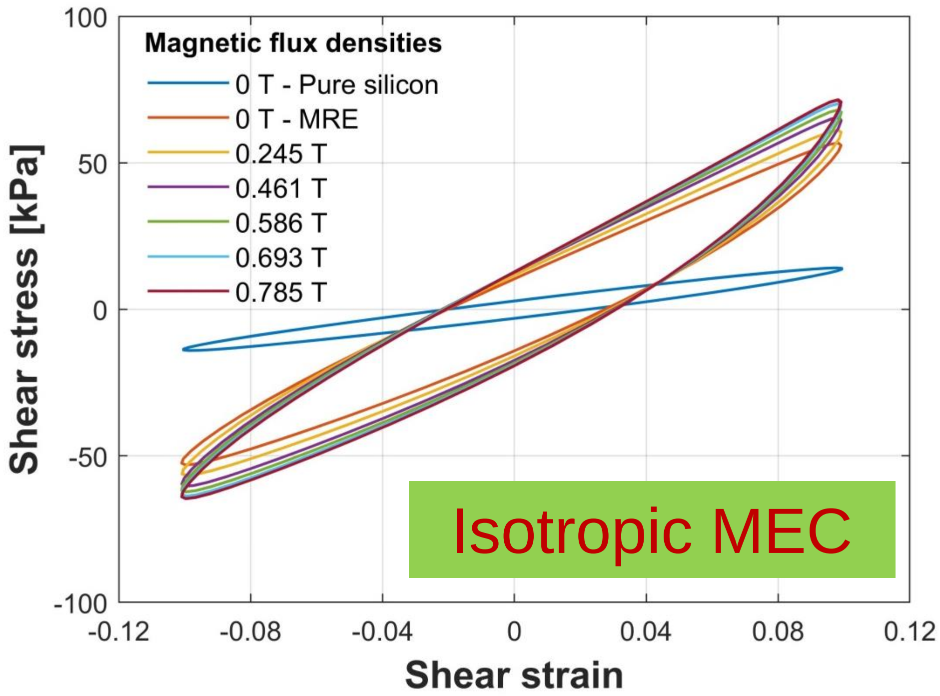
Double-lap shear test of magneto-sensitive elastomer composite (MEC)

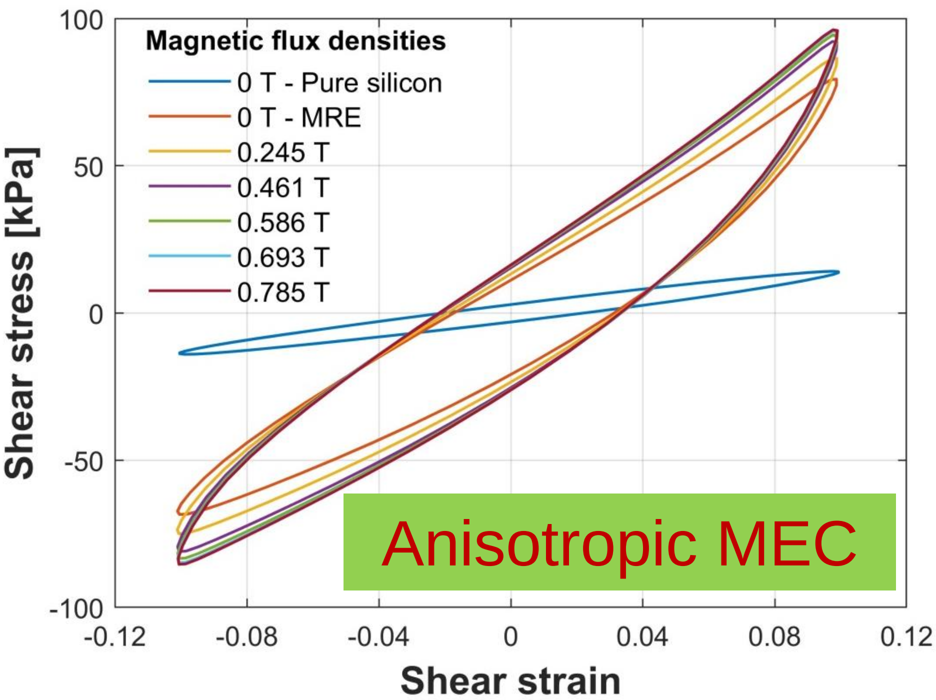
Displacement: u(t) Force: F(t)

Shear stress: $\tau(t) = \dfrac{F(t)}{A}$ Shear strain: $\gamma(t) = \dfrac{u(t)}{h}$



Typical shear stress-strain hysteresis loops

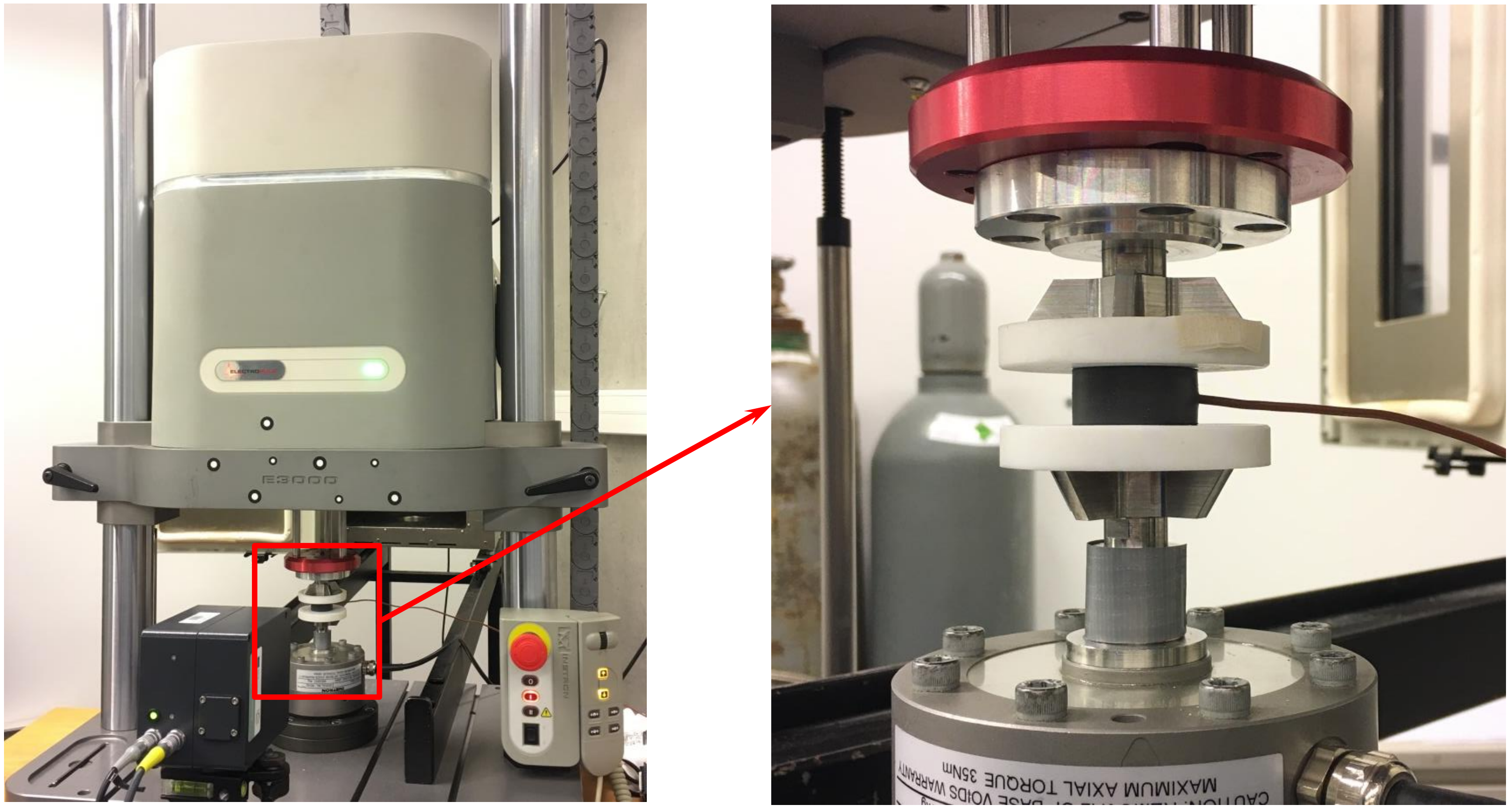




6.4. Mechanical testing of advanced materials

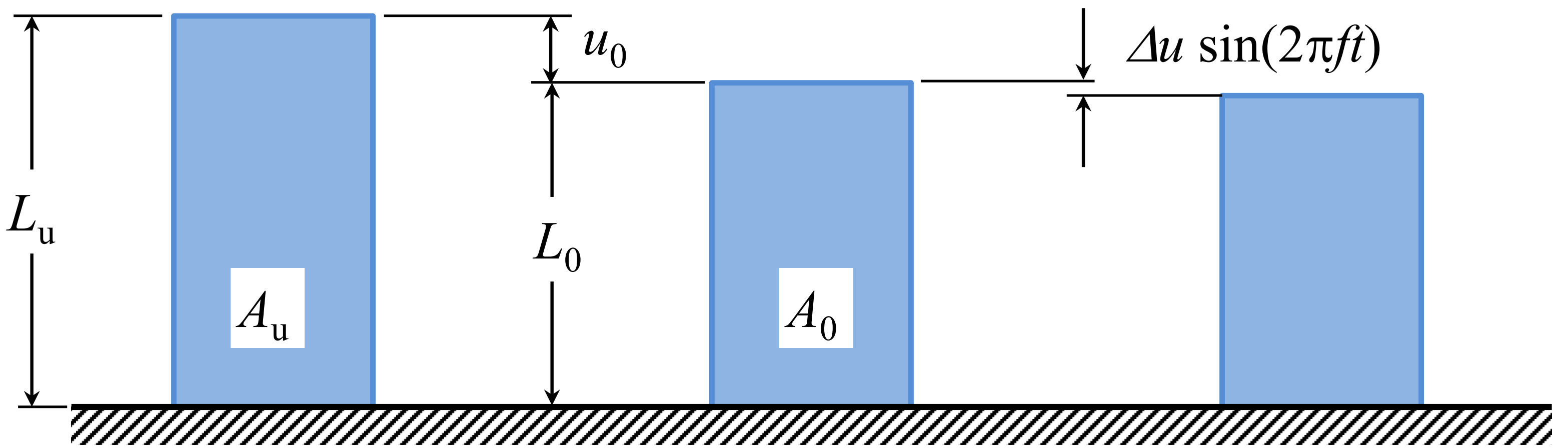
Cyclic compression test of isotropic MEC

The cyclic compression test for isotropic MEC samples was conducted under harmonic sinusoidal loading for 120 min at different pre-strains from 5 to 20%, various strain amplitudes from 1 to 5%, and frequencies from 10 to 50 Hz using Instron Electropuls E3000 testing system.



Tran Huu Nam, et al. "Self-heating and dynamic mechanical behavior of silicone rubber composite filled with carbonyl iron particles under cyclic compressive loading." *Journal of Composite Materials* 55.28 (2021): 4273-4292.

Dynamic compressive deformations of a test specimen



- Sinusoidal displacement controlled loading $u(t)$: $u(t) = u_0 + \Delta u \sin(2\pi ft)$
- Strain response $\varepsilon(t)$:

$$\varepsilon(t) = \frac{u(t)}{L_0} = \varepsilon_0 + \Delta\varepsilon \sin(2\pi ft),$$

Pre-strain $\varepsilon_0 = u_0 / L_0$, *Strain amplitude* $\Delta\varepsilon = \Delta u / L_0$

- Force response $F(t)$ is approximated as a harmonic sinusoidal function:

$$F(t) = F_0 + \Delta F \sin(2\pi ft + \delta)$$

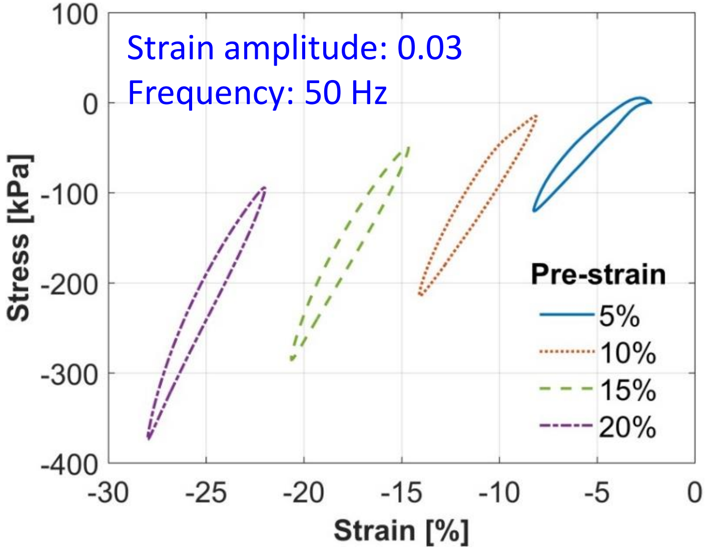
δ is a phase shift angle (loss angle)

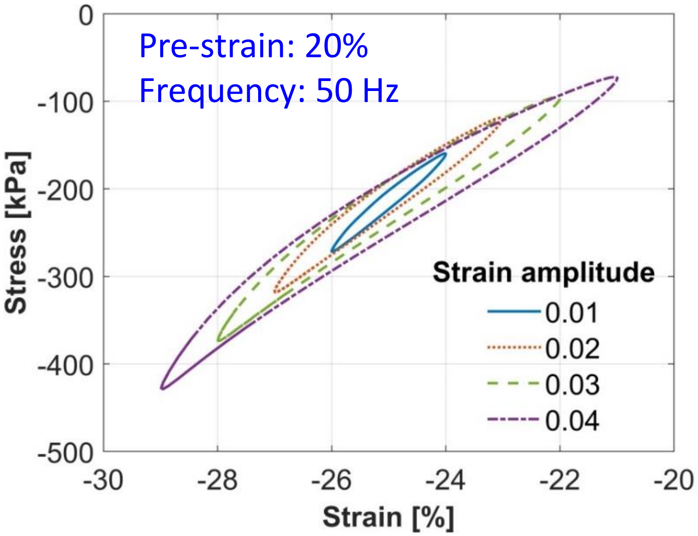
- Stress response σ(t):

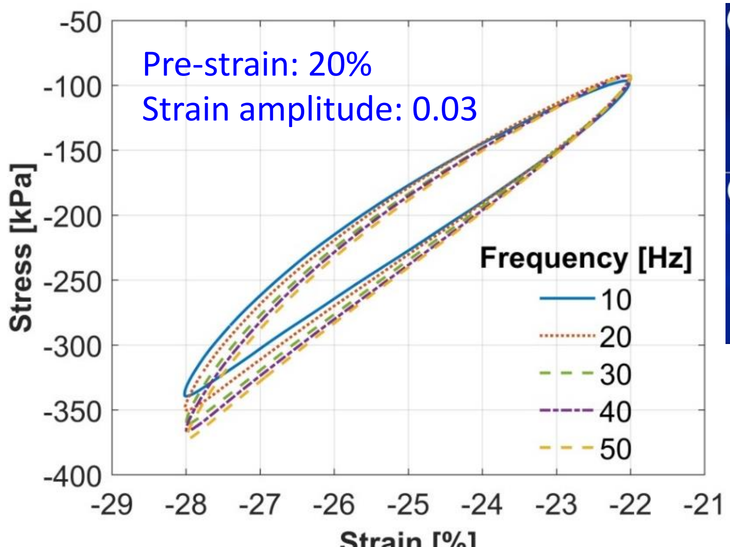
$$\sigma(t) = \frac{F(t)}{A_0} = \sigma_0 + \Delta\sigma\left[\cos(\delta)\sin(2\pi ft) + \sin(\delta)\cos(2\pi ft)\right]$$

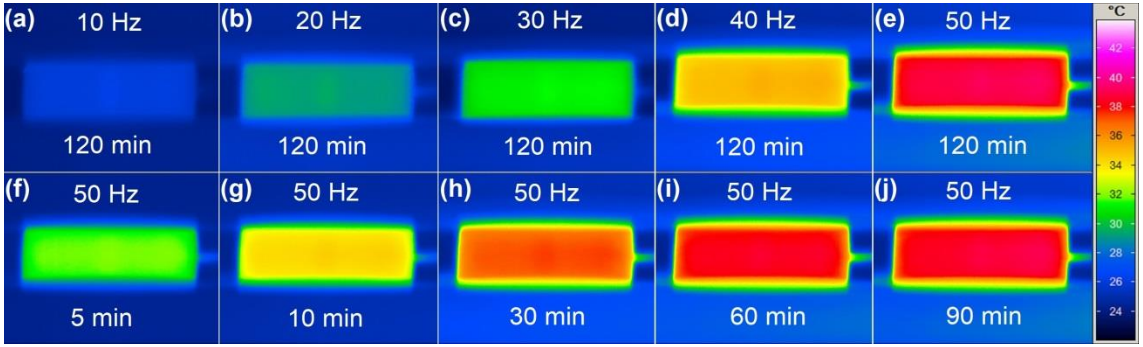
6.4. Mechanical testing of advanced materials

Dynamic compressive properties of isotropic MEC



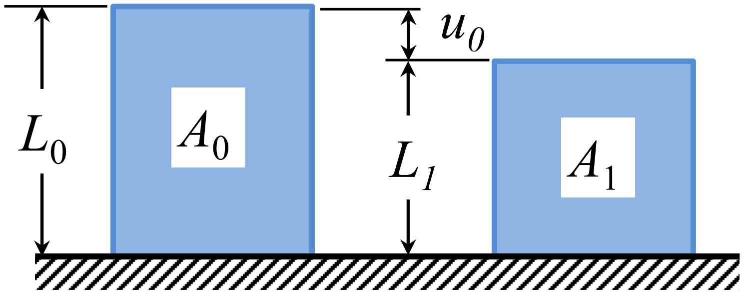




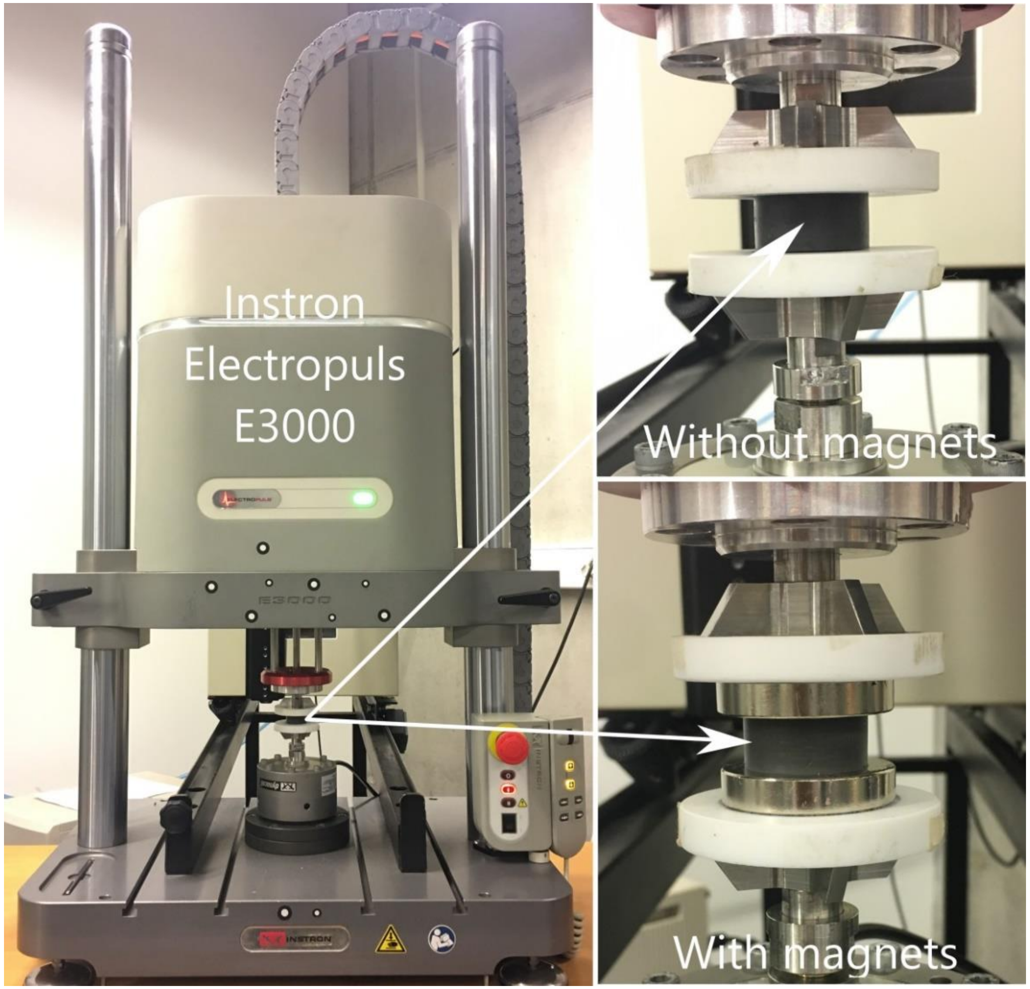


Surface plots showing the surface temperature distribution on the SRC sample loaded with the pre-strain of 20%, the strain amplitude of 3%, and different frequencies at various periods.

Compressive relaxation test of isotropic MEC



The experimental setup of the compressive stress relaxation test for the isotropic MEC sample

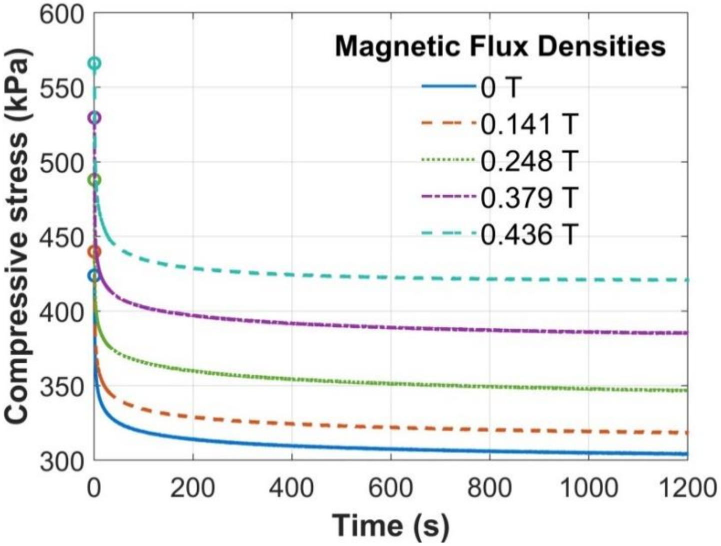


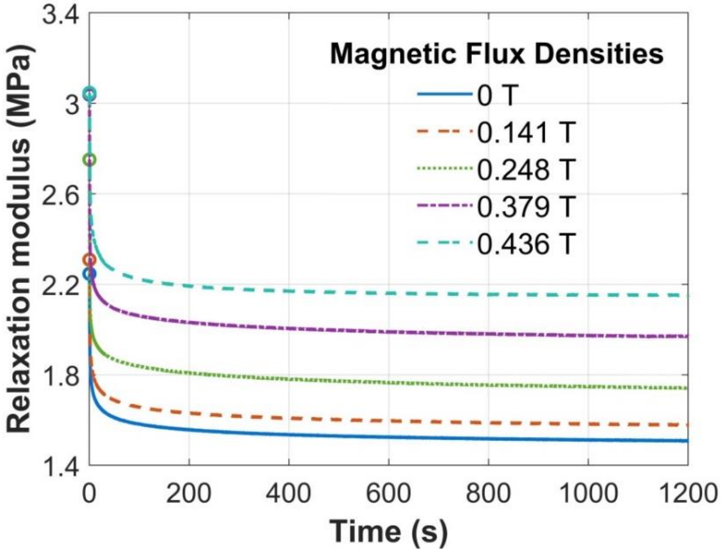
Magnetic flux densities (MFDs): 0-0.436 T.

In a relaxation test, a constant strain $\varepsilon = \varepsilon_0 = u_0/L_0$ is applied and the stress $\sigma(t)$ is measured. The relaxation modulus is estimated using the formulation $G(t) = \sigma(t)/\varepsilon_0$.

Tran H. Nam, I. Petríková, and B. Marvalová. "Experimental and numerical investigation of compression stress relaxation of isotropic magneto-sensitive elastomeric composite.“ *Constitutive Models for Rubber XII: Proceedings of the 12th European Conference on Constitutive Models for Rubber (ECCMR 2022), September 7–9, 2022, Milano, Italy*. CRC Press, 2022.

Compressive relaxation test of isotropic MEC



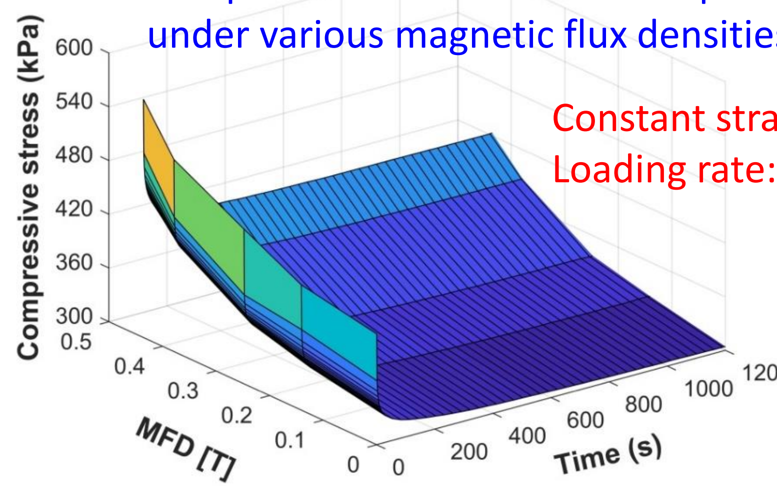


(a)

Compressive stress of the isotropic MEC under various magnetic flux densities at RT.

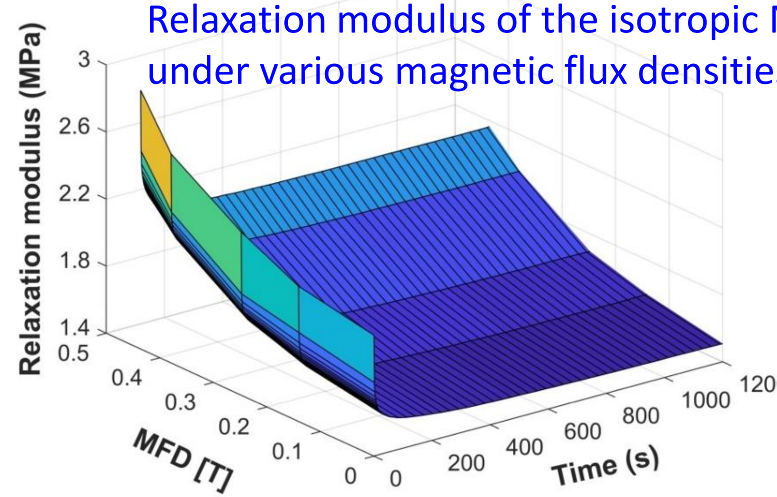
Constant strain: 20%

Loading rate: 1.0/s



(b)

Relaxation modulus of the isotropic MEC under various magnetic flux densities at RT.

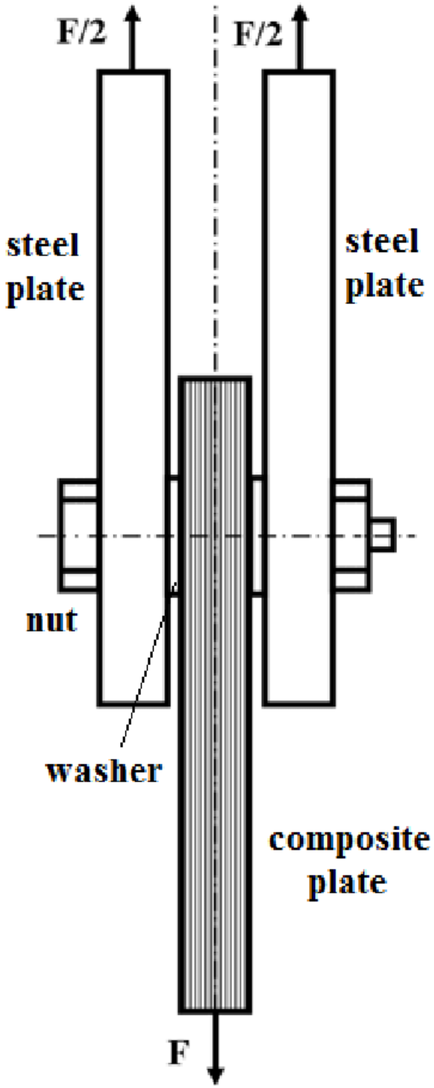


Several Test Methods For Composite and Advanced Materials

- Bearing Testing
- Fracture Mechanics Testing
- Adhesives Testing
- Test Methods for Sandwich Composites
- Non-Destructive Testing

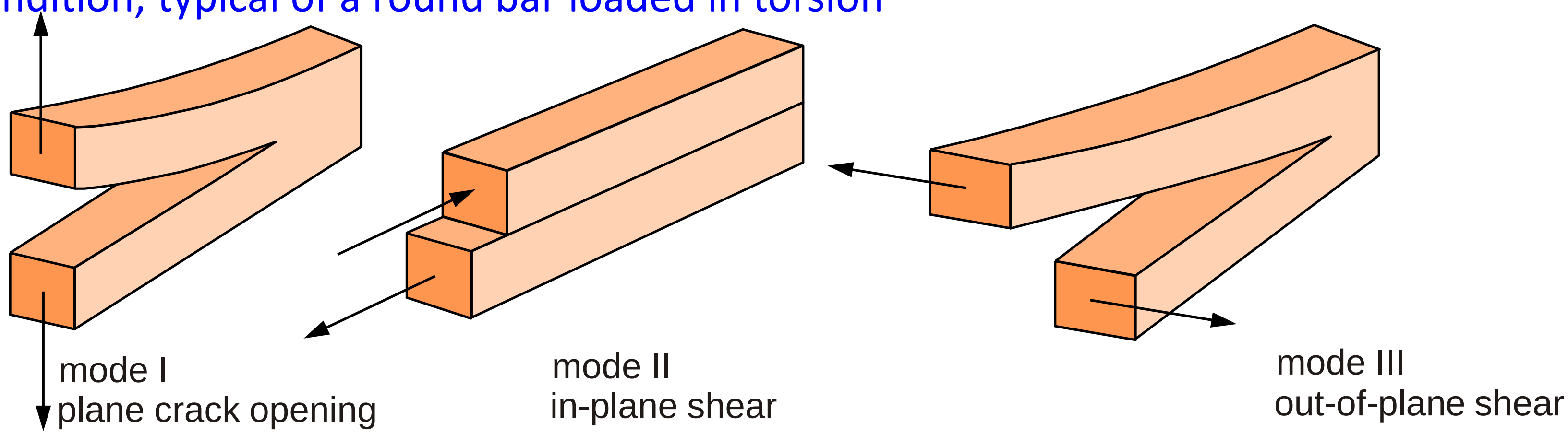
Bearing Testing

- Laminate test
- Utilizes specified bolted joint configuration
  - Single shear
    - One bolt
    - Two bolt
  - Double shear
- Used to compare materials and provide design values
  - Not meant to be representative of actual joint designs
  - Yield and ultimate bearing strength
  - Governed by ASTM D 5961



Fracture Mechanic Testing

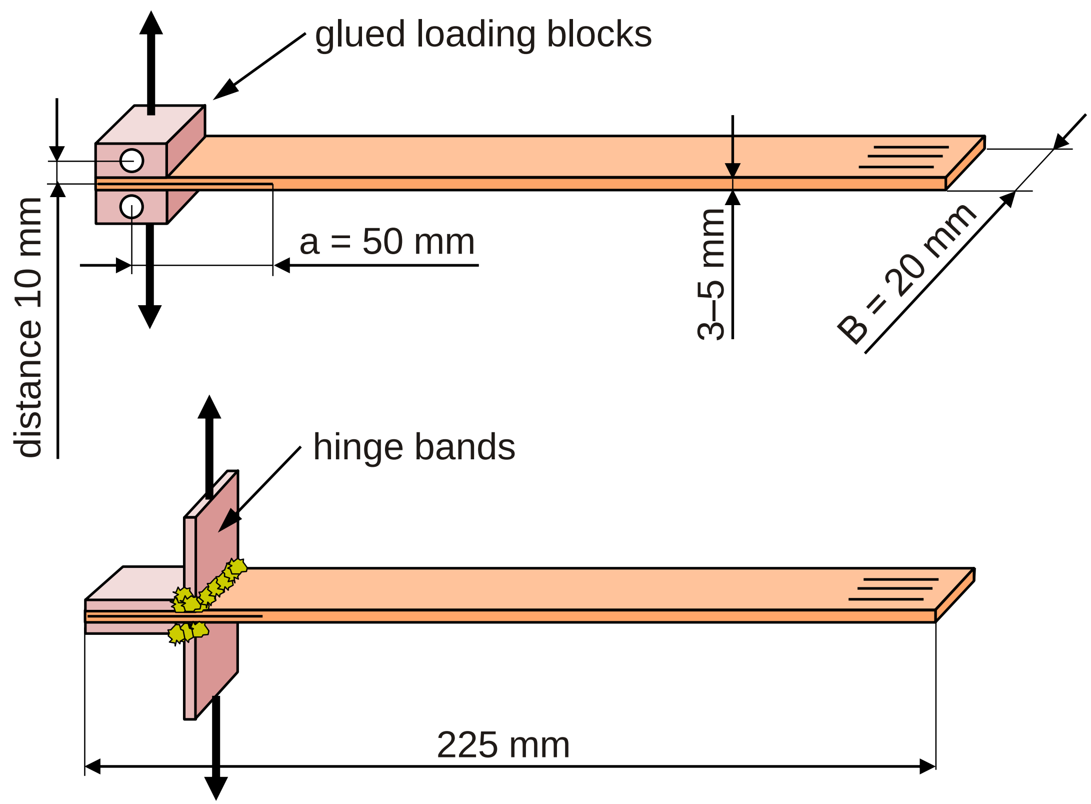
- Determine propagation characteristics of existing cracks/delaminations
- Considers three modes of crack growth
  - Mode I –opening or extension: Opening mode (a tensile stress normal to the plane of the crack). The load is applied normal to the crack plane, tends to open the crack.
  - Mode II –shear: Sliding mode (a shear stress acting parallel to the plane of the crack and perpendicular to the crack front), corresponds to in-plane shear loading and tends to slide one crack face with respect to the other
  - Mode III –tearing or twist: Tearing mode (shear stress acting parallel to the plane of the crack and parallel to the crack front). It is associated with a pure shear condition, typical of a round bar loaded in torsion



Fracture Mechanic Testing

- Mode I –opening or extension: ASTM D 5528

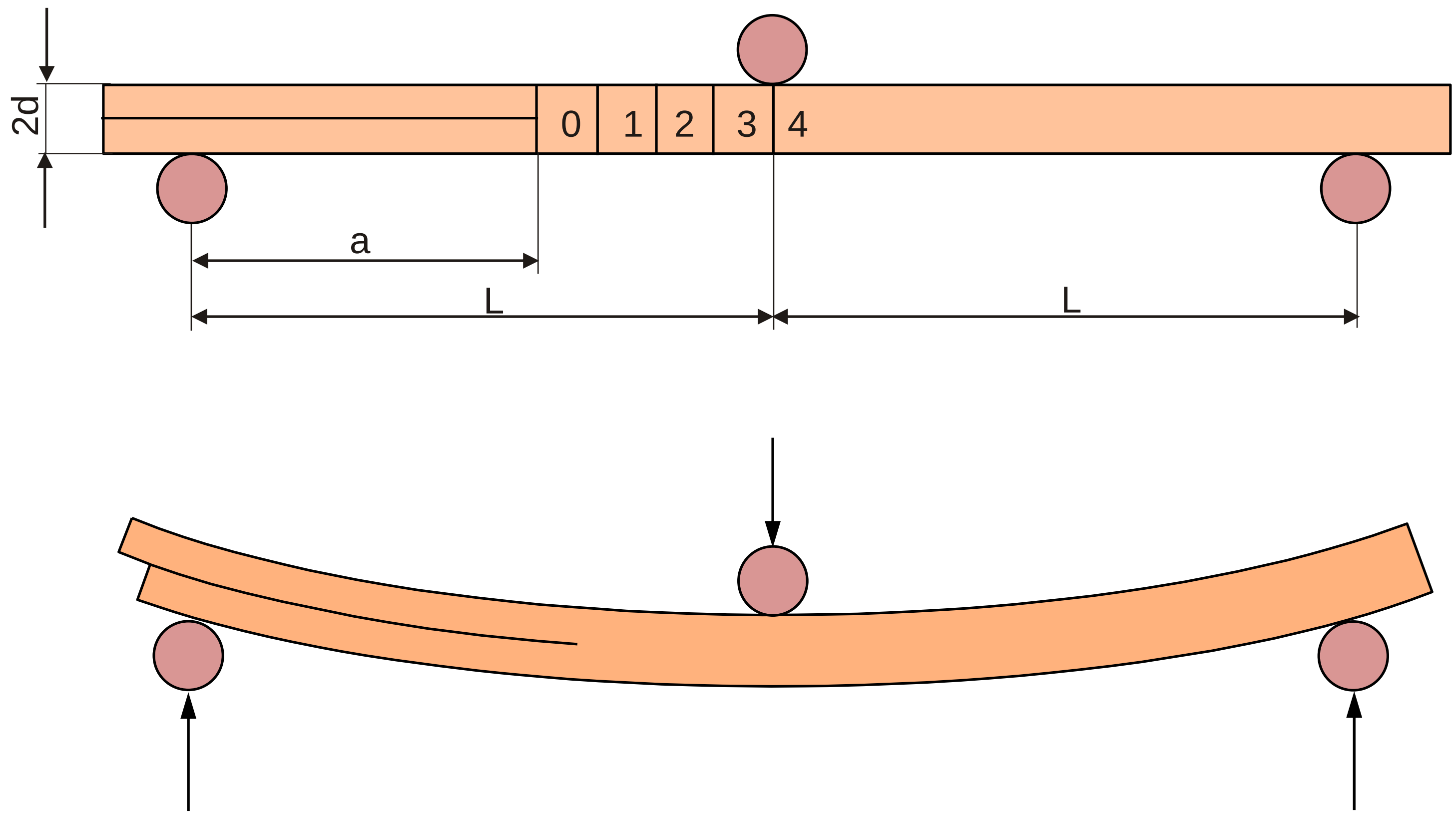
Double cantilever beam flexural test (tension)



Fracture Mechanic Testing

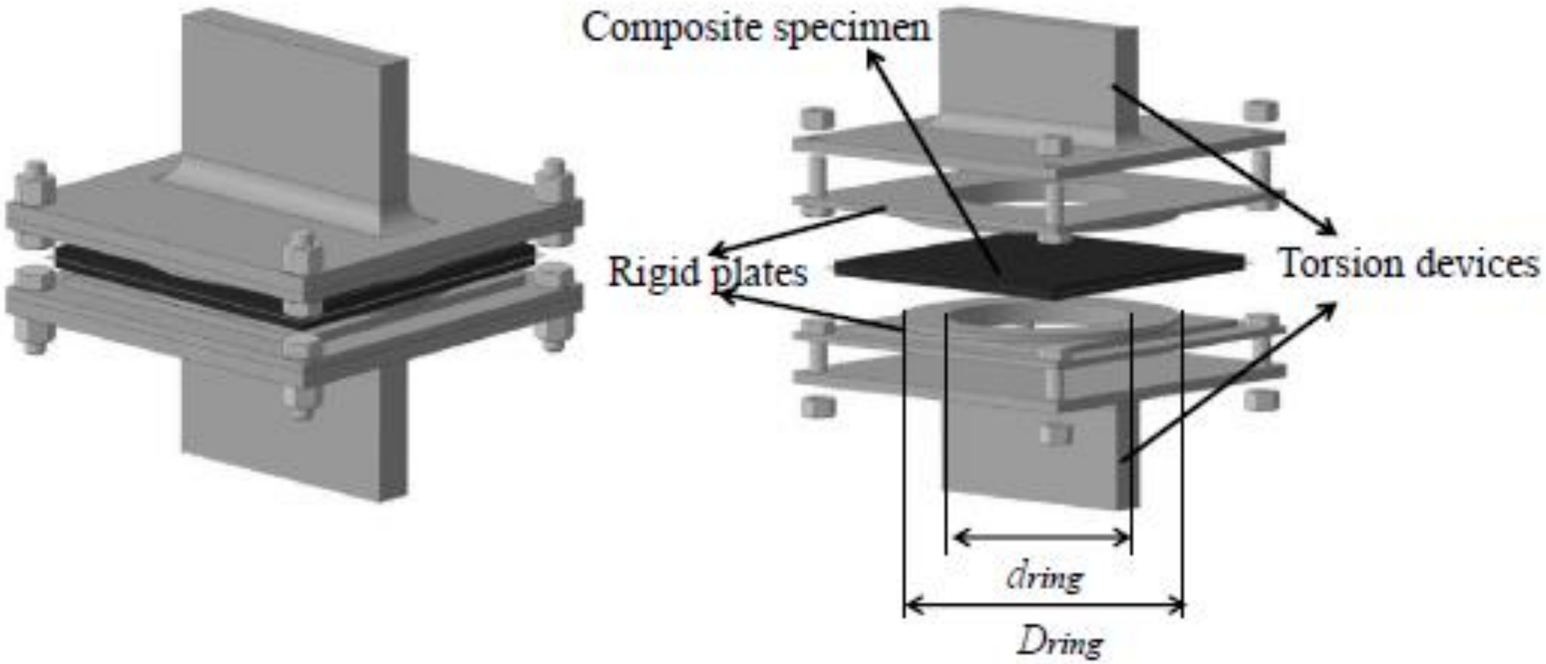
- Mode II –shear

End-notch flexural (ENF) test



Fracture Mechanic Testing

- Mode III –tearing or twist

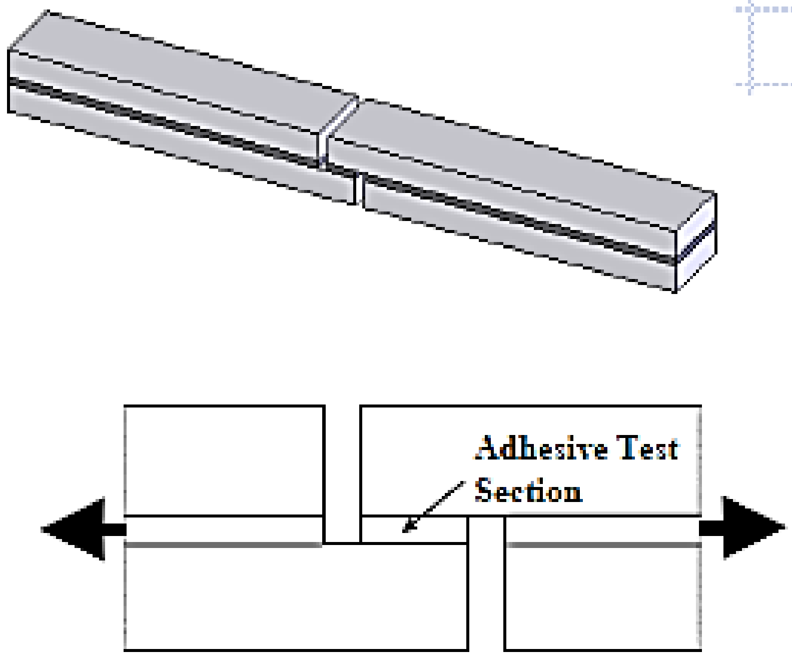


Edge Ring Crack Torsion test device

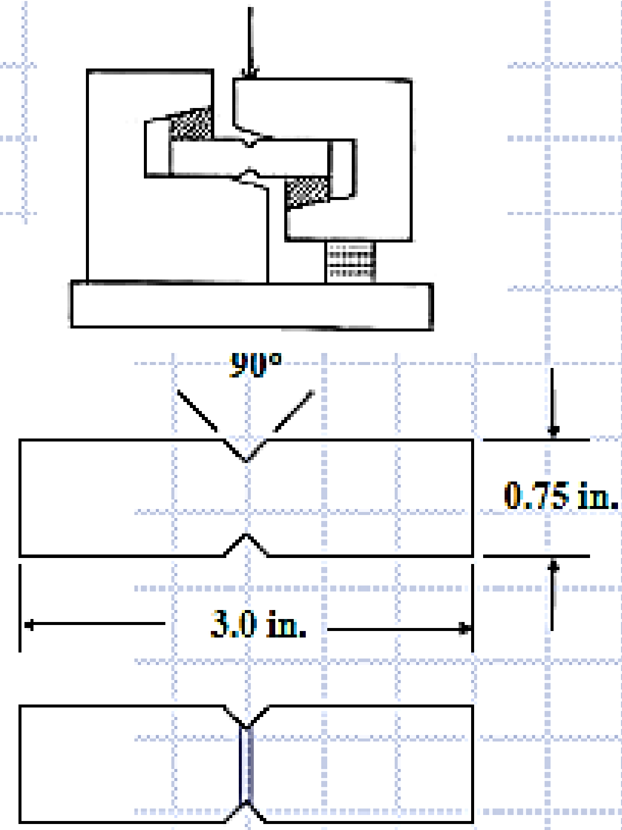
Adhesive Testing

- Adhesive characterization testing
  - Typically tensile and shear testing
  - Provides adhesive stiffness and strength data
    - Ultimate strength, initial tangent modulus
    - Stress versus strain curves
  - Used for design & analysis, comparisons
- Bonded joint characterization testing
  - Representative of actual joint to be used
  - Typically do not follow standardized test methods

Adhesive Testing: Examples of Shear Test Methods



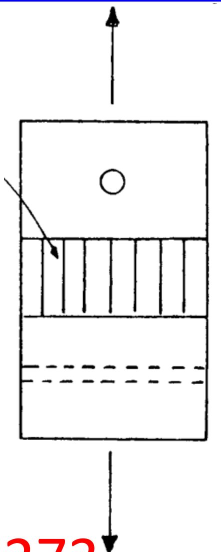
ASTM D 5656
Thick Adherend Specimen

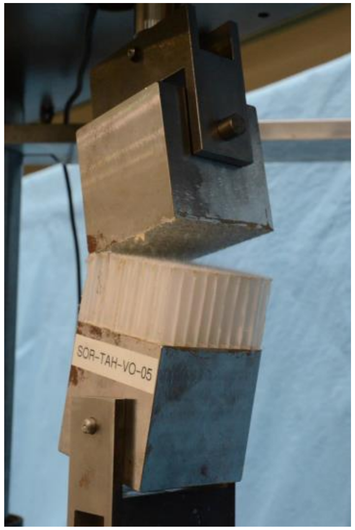


ASTM D 5379
Iosipescu Shear Specimen

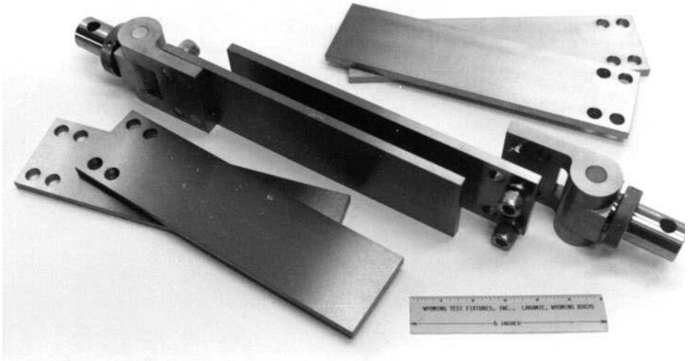
Mechanical Test Methods for Sandwich Composites

- Flatwise Tension ASTM C 297
- Flatwise Compression ASTM C 365
- Sandwich Panel Shear ASTM C 273
- Sandwich Panel Flexure ASTM C 393
- Climbing Drum Peel ASTM D 1781



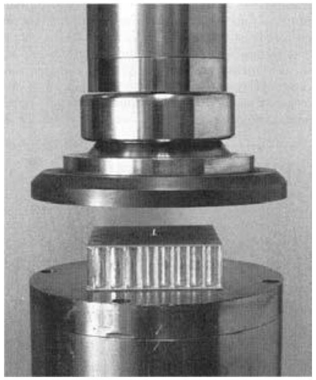


Sandwich Panel Shear Test ASTM C 273



Tension Loading

Compression Loading



6.5. Other Test Methods

Non-Destructive Testing (NDT)

- Find defects/anomalies that may affect composite performance:
  - Inhomogeneities within the materials
  - Fiber breakage
  - Resin micro-cracking
  - Voids and porosity
  - Delaminations
  - Cure deficiencies
- Functions of Non-Destructive Testing (NDT)
  - initial inspection of test samples:
    - confirmation of structural integrity
  - monitoring sample tests in progress:
    - monitoring components under service loads
    - especially where changes occur over time:
  - analysis of reasons for failure

Typical NDT Techniques For Composite and Advanced Materials

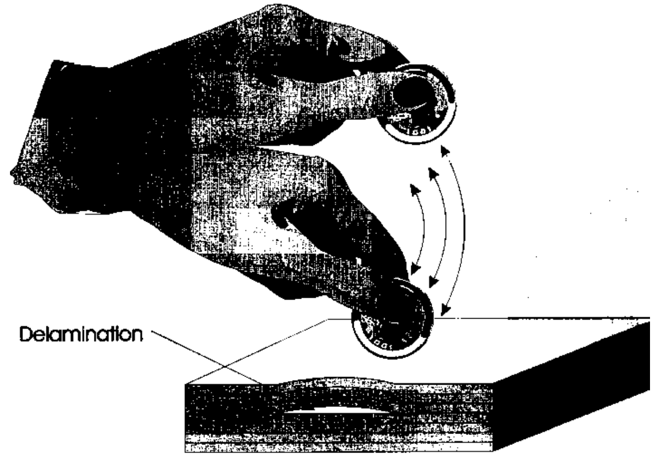
- Visual Inspection
- Tap Testing
- Ultrasonic Methods
- X-Ray
- Thermography
- DIC -Digital Image Correlation

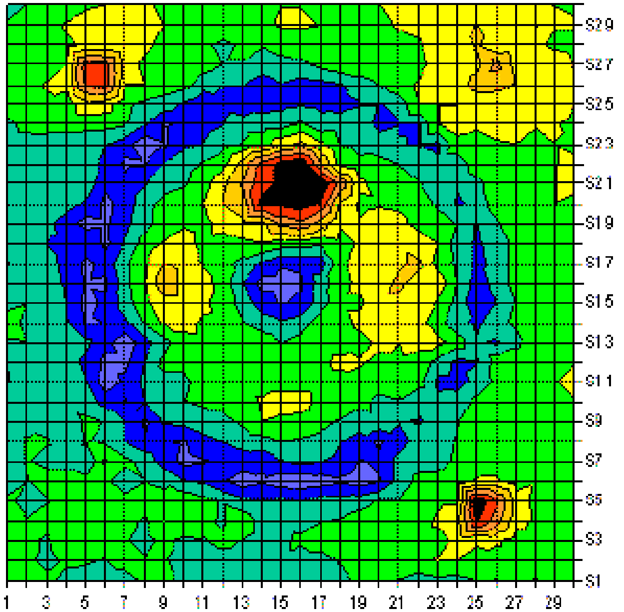
Visual Inspection

- Easiest system to use (eye, microscope)
- Can visually detect…
  - Surface damage (ex: abrasions, cuts, dents)
  - Blisters, bubbles on surface
  - Porosity, delaminations (inspection of edges)
- First line of investigation

Tap Testing

- Follow-on to visual inspection
- Based on ability to `hear’ sound differences
- Effective in mapping delamination areas
- Used extensively because of ease and cost
- Computer-aided/electronic tap testers available for commercial usage

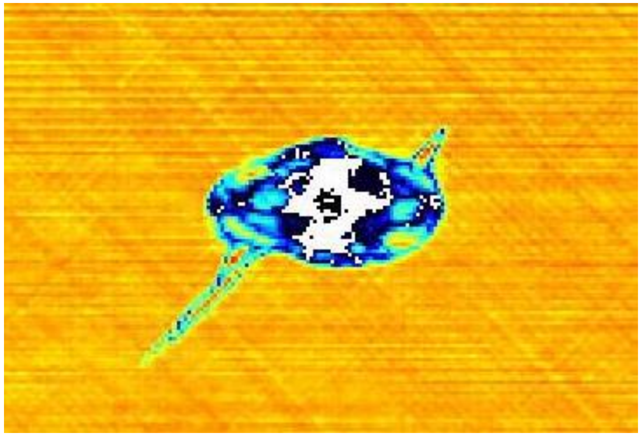


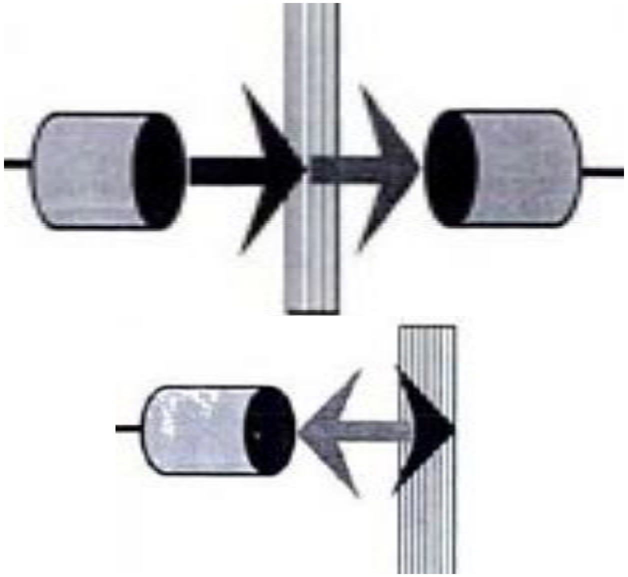


http://www.asi-nde.com

Ultrasonic Test Methods

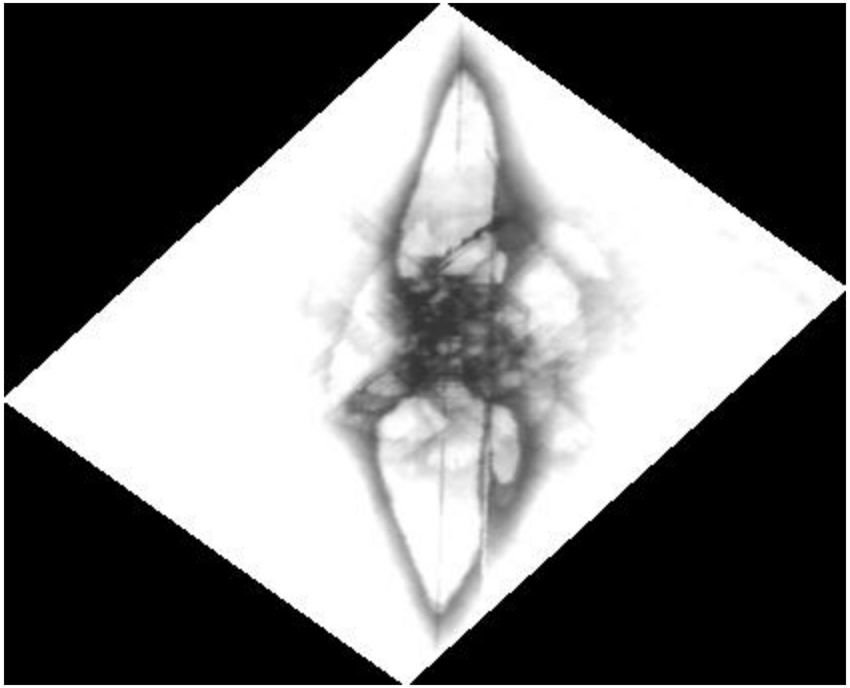
- Through-transmission
  - Requires access to both sides of composite structure
- Pulse echo
  - Requires access from only one side of composite structure
  - More applicable to field inspections





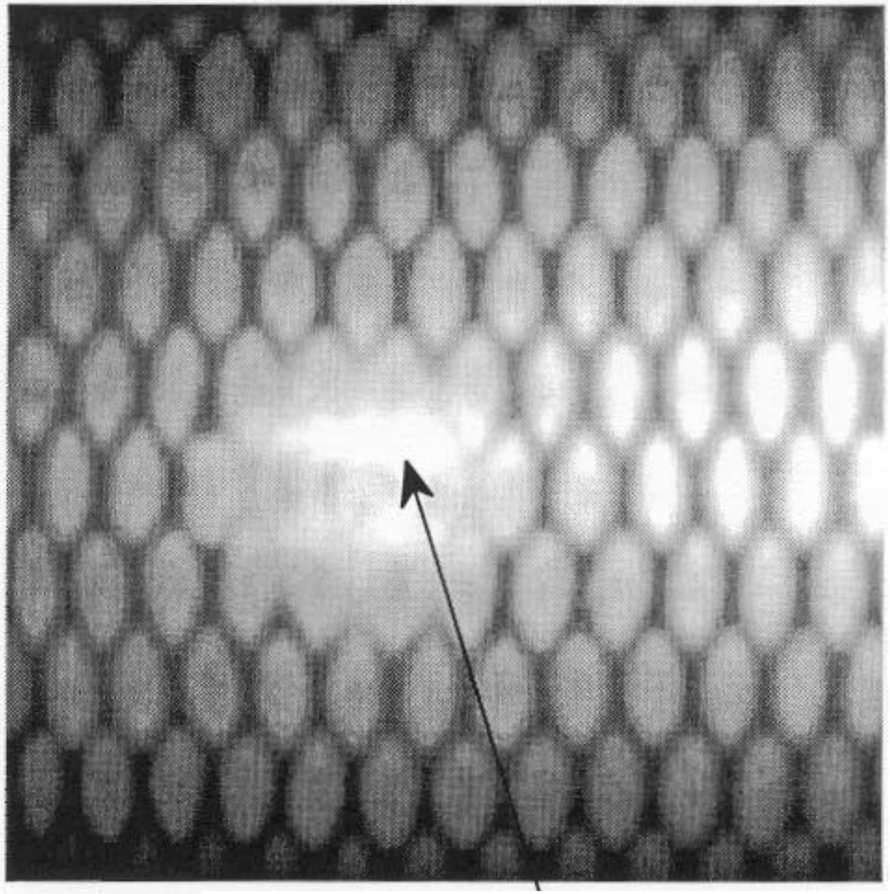
X-Ray Inspection

- Detects density changes
- Well suited for bonded interfaces
- Can locate delaminations, voids, porosity, moisture, inclusions
- Technique in use many years (rocket motors, nozzles)



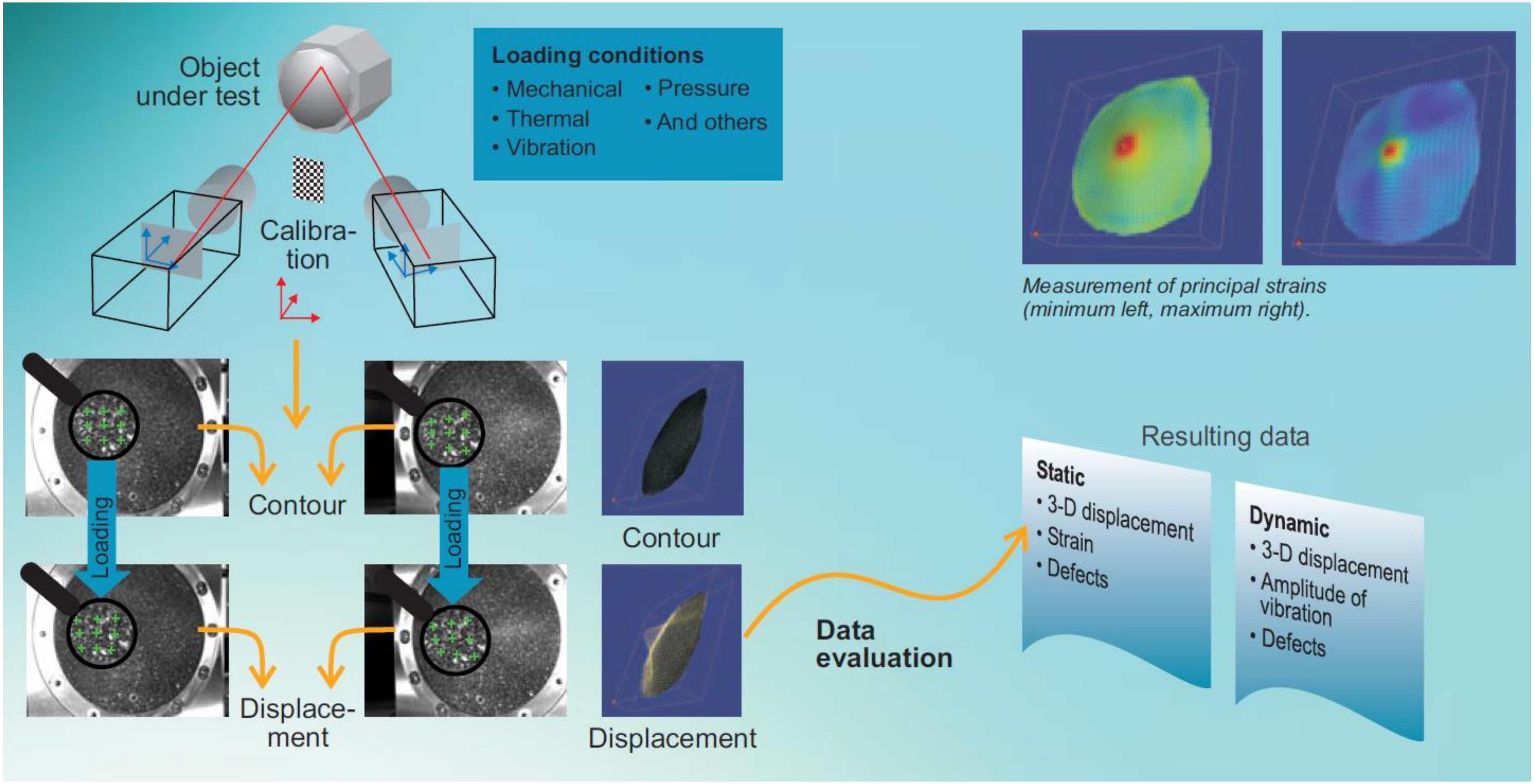
Thermography

- Uses heat transfer ---not sound waves
- Requires infrared video camera
- Measures effects from thermal changes
- Useful for locating delaminations and contamination (moisture, solvents)
- Potential field usage



Delamination

DIC - Digital Image Correlation



https://www.dantecdynamics.com/measurement-principles-of-dic

References

1. Autar K. Kaw. Mechanics of Composite Materials. 2nd edition, Taylor & Francis, 2006.
2. I.M. Daniel and O. Ishai. Engineering Mechanics of Composite Materials. Oxford University Press, 2006.
3. Robert M. Jones. Mechanics of Composite Materials. 2nd edition, Taylor & Francis, 1999.
4. Vladislav Laš. Mechanika kompozitních materiálů. Západočeská Univerzita V Plzni, 2004.
5. Swanson, S.R., Introduction to Design and Analysis with Advanced Composite Materials, Prentice Hall, Englewood Cliffs, NJ, 1997.
6. Ugural, A.C. and Fenster, S.K., Advanced Strength and Applied Elasticity, 3rd ed. Prentice Hall, Englewood Cliffs, NJ, 1995.
7. Buchanan, G.R., Mechanics of Materials, HRW Inc., New York, 1988.
8. S. Kedari. Metal matrix composites. Gogte Institute of technology, 2014.
9. N. Kumar. A seminar presented on application and properties of ceramics matrix composite. Jadavpur University Kolkata, 2016.
10. S. Dahiya. Carbon-carbon composites, 2017.