Experimental Mechanics of Composites

Prof Jack Gillespie
201 CMSL
gillespi@udel.edu
302 831 8702

Lecture Dates **Tuesday: 106 CMSL** **12:30-1:45pm**		**Lab Dates (Meet in 106 for prelab discussion)** **Wednesday** **3:35-4:50pm**	 **Thursday** **12:30-1:45pm**	 **Friday** **3:35-4:50pm**
2/12	Introduction HW Online Safety Training Read Chapters 1 and 3 EHS Online Training	2/13 CCM Safety Training and Lab Tour (panel lay-up, bagging, autoclave, specimen fab, NDE, microscopy)) Mandatory for lab access; Send certificates to Johnny	2/14	2/15
2/19	Intro to Composites Experimental Mechanics I	2/16 Lab 1: Panel lay-up and processing	2/17	2/18
2/26	Experimental Mechanics II Read Chapter 8	2/27 Lab 1: Quality Lab: NDE, Microscopy, Fiber Volume/Void Content, Strain Gaging	2/29	2/29
3/5	Micromechanics HW1: Predict and Compare Properties Read Chapter 9	3/6 Lab 2: 0 and 90 degree tension Lab Lab 1 Report Due	3/7	3/8
3/12	Anisotropic Elasticity HW2: Predict and Compare Compression Properties Read Chapter 10	3/13 Lab 3: 0 and 90 compression Lab Lab2 Report Due (include HW1)	3/14	3/15
3/19	Laminate Mechanics HW3: Predict and Compare Inplane Shear Properties Read Chapter 2	3/20 Lab 4: +-45 Tension/Inplane Shear Lab Lab 3 Report Due (include HW2)	3/21	3/22
3/26	Software Demo For Laminates HW 4 Predict Laminate Properties	3/27 Lab 4 Due (include HW3)	3/28	3/29
4/1	Spring Break Week	No lecture/no labs		
4/9	Flexure and Shear Read Chapter 11	4/10 Lab 5: Short Beam Shear and Flexure Lab	4/11	4/12

4/16	Strength and Fracture	4/17 Lab 5: Short Beam Shear and Flexure Lab	4/18	4/19
4/23	Notch Strength/Interlaminar Fracture Read Chapter 17	4/24 Lab 5 Report Due HW 4 Due Lab 6: Notch Strength	4/25	4/26
4/30	Fibers and Interphases Read Chapter 7	5/1 Lab 6 Report Due Lab Tour/Demo	5/2	5/3
5/7	DMA/Thermal Analysis	5/8 Lab Demo	5/9	5/10
5/14	Review	5/15 No Lab	5/16	5/17
5/21	Final Exam			

Notes:

- **Each student should get hands-on experience testing samples**
- **Be sure to read the ASTM standards before each lab. You are expected to follow these test procedures.**
- **Be sure to record load cell, cross-head rates, strain gage type (and gage factor) for inclusion in your lab report.**
- **Students are encouraged to take pictures of test set-up and specimens before and after testing to record failure modes. It is fine to share these images.**
- **Files of autoclave runs, C-scans, images will be provided for Lab 1.**
- **Each lab group will test 3-6 samples. A total of 6-10 replicates will be tested.**
- **Eacn student will be given data files for all replicates (including specimen dimensions, etc) on Friday afternoon by Johhny.**
- **Each student is required to write individual lab reports including data from all replicates (and calculate statistics such as average, standard deviation and coefficient of variation for properties)**
- **HW's are intended to predict properties measured in the lab. HW's should be included in the lab report as an appendix. Compare predictions to measurments.**
- **Lab reports are due on Fridays and should be emailed to gillespi@udel.edu**

Grading

Labs (6): 50%

HW (4): 25%

Final: 25%

Resources:

Textbook: Characterization of Advanced Composite Materials, 4th Edition, Carlsson et al.

ASTM Standards: University Libarary

CCM SAFETY TRAINING PROCEDURES
(Need to be completed before access to labs)

CCM Safety Training: Given by Johnny this week during labs.

Advanced Chemical Hygiene/Right to Know Training

1. If you have completed training within the past 12 months, forward your certificates to Johnny Thiravong at johnnyde@udel.edu
2. Go to: http://www1.udel.edu/ehs/training/bioraft_ehsa_temp.html
3. PleaLogin with your UDelNet ID and password
4. Select Training on the left
5. Select Course Directory
6. Select Advanced Chemical Hygience/RTK Training
7. Email your results to Johnny Thiravong at johnnyde@udel.edu

Chemical Waste Disposal Training

1. If you have completed training within the past 12 months, forward your certificates to Johnny Thiravong at johnnyde@udel.edu
2. Go to: http://www1.udel.edu/ehs/training/bioraft_ehsa_temp.html
3. Login with your UDelNet ID and password
4. Select Training on the left
5. Select Course Directory
6. Select Chemical Waste Disposal
7. Email your results to Johnny Thiravong at johnnyde@udel.edu

Class Contact Info

Key Contact: Johnny Thiravong

NAME	EMAIL	PHONE
Durbano, Steve	sdurbano@udel.edu	302-831-2672
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Shevchenko, Nick	shevchen@udel.edu	302-831-6105
Thiravong, Johnny	johnnyde@udel.edu	302-831-2672
Yiournas, Art	yiournas@udel.edu	302-831-1598

MSEG 610 - 010 (15696)

Experimental Mechanics of Composites (Lecture)

Days and Times	Room	Instructor	Dates
Tu 12:30PM-1:45PM	Center for Composite Materials	John Gillespie	02/11/2019 - 05/20/2019

Enrollment Status Enrolled

Enrollment Capacity 6 **Enrolled** 6

Enrolled Students

	ID	Name	Audit	Units	Program and Plan	Level
1	702420778	Chaudhari,Amit		3.00	Engineering - Mechanical Engineering	Doctoral
2	702481658	Lee,Junghyun		3.00	Engineering - Materials Science &Engineering	Doctoral
3	702386071	Mishkhas,Ali Tarek A		3.00	Engineering - Mechanical Engineering BME/Civil Engineering	Sophomore
4	702493726	Muhammed,Faheem Hameen		3.00	Engineering - Materials Science &Engineering	Doctoral
5	702466799	Premkumar,Abishek Jerome Rajakumar		3.00	Engineering - Materials Science &Engineering	Master's
6	702212051	Swain,Zachary Raymond		3.00	Engineering - [illegible]	Senior

Enrolled Students

	ID	Name	Audit	Units	Program and Plan	Level
1	702418042	Busch,Casey		3.00	Engineering - Chemical Engineering BCHE/Materials Science &Engineering	Junior
2	702289245	Meyer,Keith		3.00	Engineering - Mechanical Engineering BME/Computer Science/Integrated Design/Mathematics/Materials Science &Enginee	Senior
3	702438270	Minnigh,Evan Alexander		3.00	Engineering - Chemical Engineering BCHE/Materials Science &Engineering	Junior
4	702429640	Pranda,Paula Ann		3.00	Engineering - Chemical Engineering BCHE/Chemistry/Honors/Nanoscale Materials	Junior
5	702373804	Tino,Emily Georgia		3.00	Engineering - Environmental Eng BENE/Materials Science &Engineering	Junior
6	702345361	Wagner,Thomas Jacob		3.00	Engineering - Chemical Engineering BCHE/Honors/Materials Science &Engineering	Senior

MSEG 610 - 021L (15912)

change class

Experimental Mechanics of Composites (Laboratory)

Days and Times	Room	Instructor	Dates
We 3:35PM-4:50PM	Center for Composite Materials	Staff	02/11/2019 - 05/20/2019

Enrollment Status Enrolled

Enrollment Capacity 2 Enrolled 2

Enrolled Students Find | | First 1-2 of 2 Last

	ID	Email	Name	Audit	Units	Program and Plan	Level
1	702420778	amitc@udel.edu	Chaudhari,Amit		0.00	Engineering - Mechanical Engineering	Doctoral
2	702481658	leejh@udel.edu	Lee,Junghyun		0.00	Engineering - Materials Science &Engineering	Doctoral

Printer Friendly Version

MSEG 610 - 020L (15910)

change class

Experimental Mechanics of Composites (Laboratory)

Days and Times	Room	Instructor	Dates
Th 12:30PM-1:45PM	Center for Composite Materials	Staff	02/11/2019 - 05/20/2019

*Enrollment Status Enrolled

Enrollment Capacity 2 Enrolled 2

Enrolled Students Find | | First 1-2 of 2 L

	ID	Email	Name	Audit	Units	Program and Plan	Level
1	702386071	mishkhas@udel.edu	Mishkhas,Ali Tarek A		0.00	Engineering - Mechanical Engineering BME/Civil Engineering	Sophom
2	702212051	zswain@udel.edu	Swain,Zachary Raymond		0.00	Engineering - Mechanical Engineering BME/Mathematics	Senior

Enrolled Students Find | | First 1-3 of 3 La

	ID	Email	Name	Audit	Units	Program and Plan	Level
1	702289245	kmeyer@udel.edu	Meyer,Keith		0.00	Engineering - Mechanical Engineering BME/Computer Science/Integrated Design/Mathematics/Materials Science &Enginee	Senior
2	702429640	papranda@udel.edu	Pranda,Paula Ann		0.00	Engineering - Chemical Engineering BCHE/Chemistry/Honors/Nanoscale Materials	Junior
3	702345361	wagnert@udel.edu	Wagner,Thomas Jacob		0.00	Engineering - Chemical Engineering BCHE/Honors/Materials Science &Engineering	Senior

MSEG 410 - 022L (15908) change class

Experimental Mechanics of Composites (Laboratory)

Days and Times	Room	Instructor	Dates
Fr 3:35PM-4:50PM	Center for Composite Materials	Staff	02/11/2019 - 05/20/2019

*Enrollment Status Enrolled

Enrollment Capacity 3 Enrolled 3

Enrolled Students Find | | First 1-3 of 3 Last

	ID	Email	Name	Audit	Units	Program and Plan	Level
1	702418042	cebusch@udel.edu	Busch,Casey		0.00	Engineering - Chemical Engineering BCHE/Materials Science &Engineering	Junior
2	702438270	eminnigh@udel.edu	Minnigh,Evan Alexander		0.00	Engineering - Chemical Engineering BCHE/Materials Science &Engineering	Junior
3	702373804	egtino@udel.edu	Tino,Emily Georgia		0.00	Engineering - Environmental Eng BENE/Materials Science &Engineering	Junior

Enrolled Students Find | | First 1-2 of 2 Last

	ID	Email	Name	Audit	Units	Program and Plan	Level
1	702493726	faheemhm@udel.edu	Muhammed,Faheem Hameen		0.00	Engineering - Materials Science &Engineering	Doctoral
2	702466799	apjerome@udel.edu	Premkumar,Abishek Jerome Rajakumar		0.00	Engineering - Materials Science &Engineering	Master's

Current:
Lecture @ 12:30 – 1:45pm: 12 Students

Wednesday Lab @ 3:35 – 4:50pm: 2 Students
Thursday Lab @ 12:30 – 1:45pm: 5 Students
Friday Lab @ 3:35 – 4:50pm: 5 Students

Need to reduce to 2 labs with 6 students/Lab

Proposed: Merge Friday into Wednesday and need 1 student to move to Thrusday

Wednesday Lab @ 3:35 – 4:50pm: 6 Students
Thursday Lab @ 12:30 – 1:45pm: 6 Students

This will allow data collected on Wednesday/Thursday to be disseminated on Friday.

T700 Carbon Fiber/Epoxy Prepreg

G-83C Data Sheet

'TORAY'
Innovation by Chemistry

This resin system provides a quick cure (290°F for 20 min) or a low temperature cure (185°F for 6 hours) with the capability to achieve class "A" surface finish. Quick cure cycles are used where high-cycle applications are required and lower temperature cure applications would be marine or where mold material is heat sensitive. G-83C can be used in a variety of other applications such as industrial and aircraft grade products.

TORAYCA®

T700S DATA SHEET

Highest strength, standard modulus fiber available with excellent processing characteristics for filament winding and prepreg. This never twisted fiber is used in high tensile applications like pressure vessels, recreational, and industrial.

FIBER PROPERTIES

		English	Metric	Test Method
Tensile Strength		711 ksi	4,900 MPa	TY-030B-01
Tensile Modulus		33.4 Msi	230 GPa	TY-030B-01
Strain		2.1 %	2.1 %	TY-030B-01
Density		0.065 lbs/in^3	1.80 g/cm^3	TY-030B-02
Filament Diameter		2.8E-04 in.	7 µm	
Yield	6K	3,724 ft/lbs	400 g/1000m	TY-030B-03
	12K	1,862 ft/lbs	800 g/1000m	TY-030B-03
	24K	903 ft/lbs	1,650 g/1000m	TY-030B-03
Sizing Type & Amount	50C	1.0 %		TY-030B-05
	60E	0.3 %		TY-030B-05
	FOE	0.7 %		TY-030B-05
	Twist	Never twisted		

FUNCTIONAL PROPERTIES

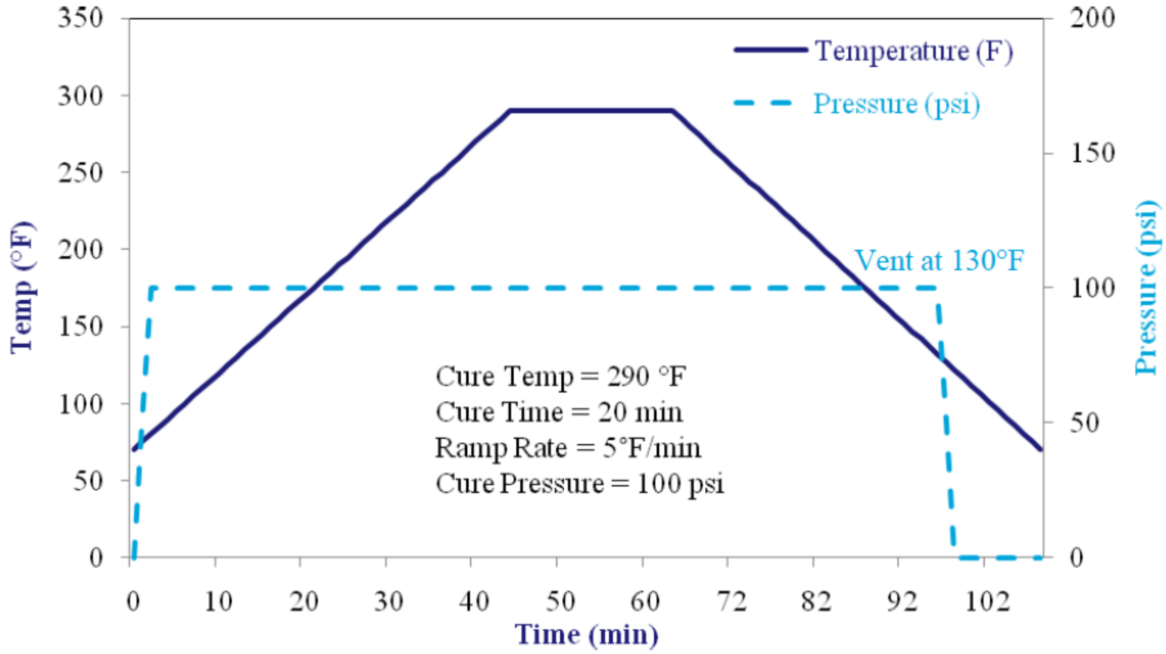
CTE		-0.38 $\alpha \cdot 10^{-6}$/°C
Specific Heat		0.18 Cal/g·°C
Thermal Conductivity		0.0224 Cal/cm·s·°C
Electric Resistivity		1.6 x 10^{-3} Ω·cm
Chemical Composition:	Carbon	93 %
	Na + K	<50 ppm

COMPOSITE PROPERTIES*

	English	Metric	Test Method
Tensile Strength	370 ksi	2,550 MPa	ASTM D-3039
Tensile Modulus	20.0 Msi	135 GPa	ASTM D-3039
Tensile Strain	1.7 %	1.7 %	ASTM D-3039
Compressive Strength	215 ksi	1,470 MPa	ASTM D-695
Flexural Strength	245 ksi	1,670 MPa	ASTM D-790
Flexural Modulus	17.5 Msi	120 GPa	ASTM D-790
ILSS	13 ksi	9 kgf/mm^2	ASTM D-2344
90° Tensile Strength	10.0 ksi	69 MPa	ASTM D-3039

* Toray 250°F Epoxy Resin. Normalized to 60% fiber volume.

Sample Quick Cure Cycle (290°F cure)



University of Delaware
Center for Composite Materials

Autoclave

Room 120

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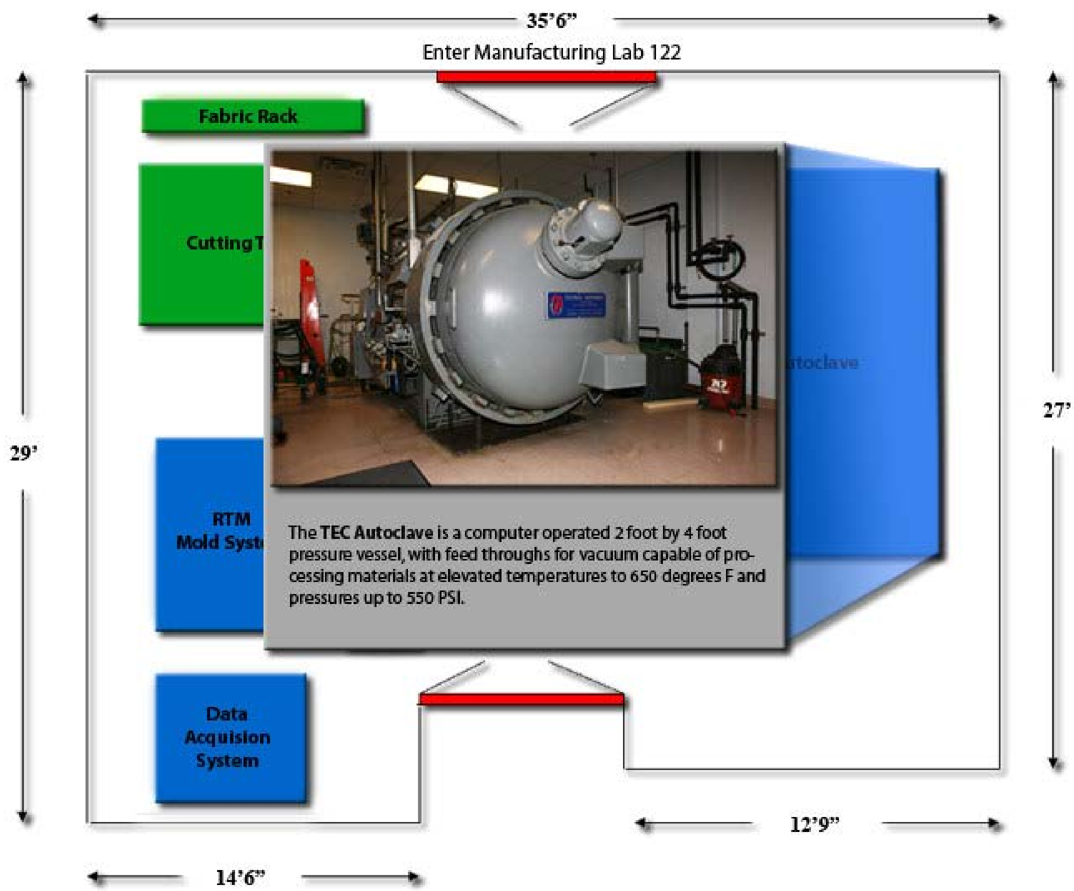
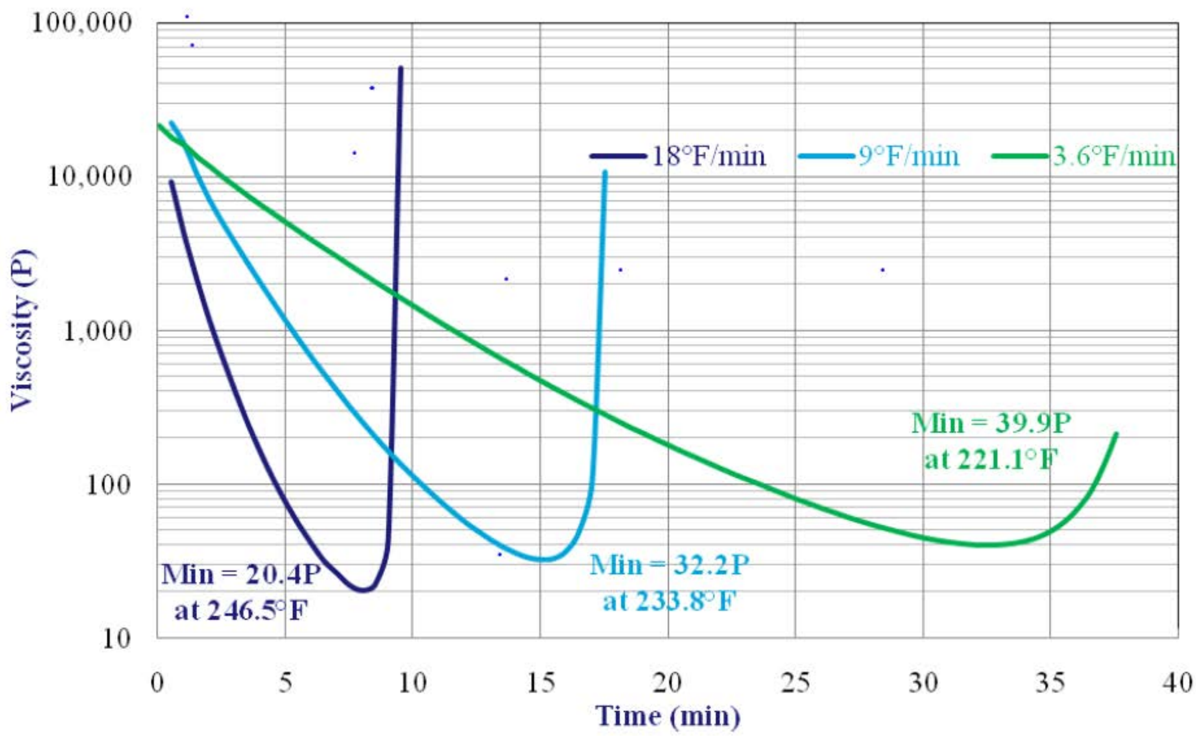
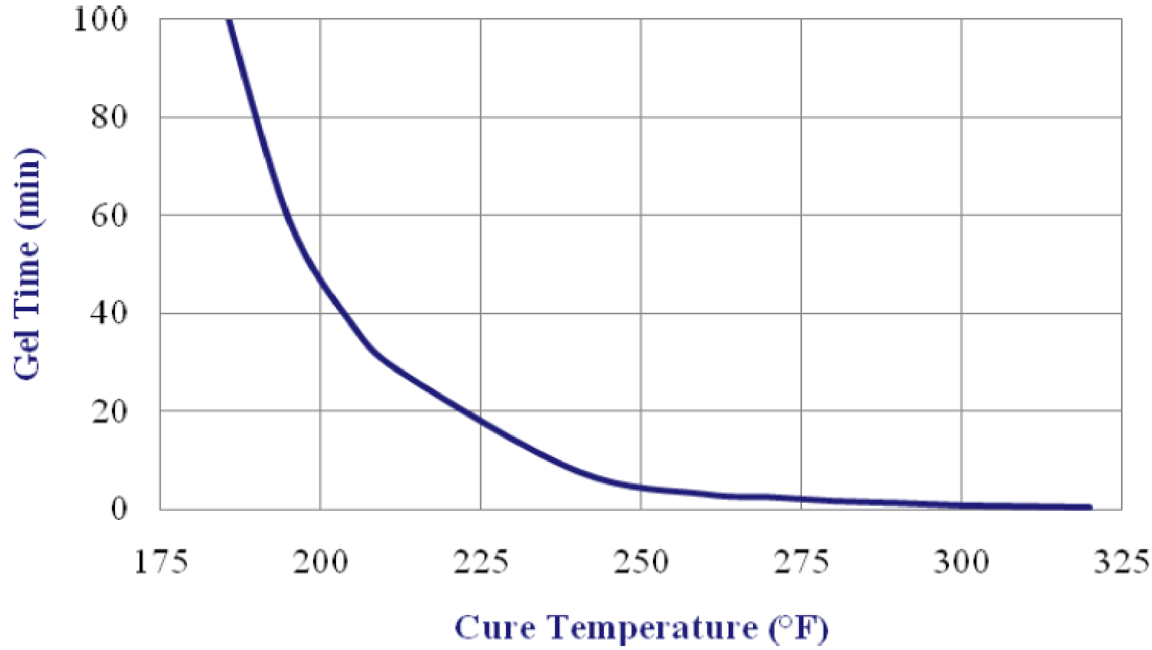


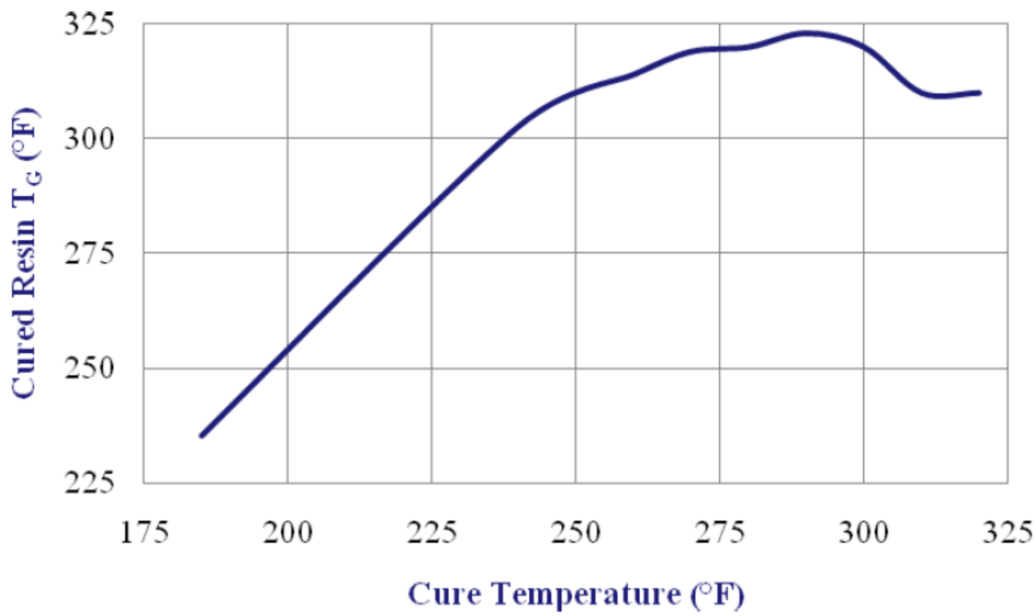
Viscosity Profile



Gel Time Cure Profile



Glass Transition Temperature (T_G) Dependency on Cure Temperature



Typical Curing Results

Cure Temperature (°F)	Gel Time (Minutes)	90% Cure Time (Minutes)	95% Cure Time (Minutes)	99% Cure Time (Minutes)	T_G (max G") (°F)
185	103.0	214.4	239.7	345.6	235
205	37.6	86.2	107.9	194.6	276
240	7.8	22.6	28.5	72.6	303
270	2.5	12.5	17.5	50.1	319
290	1.3	15.0	21.0	40.0	323
300	0.8	19.6	25.5	39.4	320

Data obtained through DMA analysis of raw resin

Neat Resin Mechanical Data

Property		Value	Test Method
Compression	*Strength (ksi)*	18.5	ASTM D 695
	Modulus (ksi)	487	
	Offset Yield (ksi)	9.5	
K_{IC}	*(psi*√in)*	1.01	ASTM D 5045-99
Flexure	*Strength (ksi)*	21.2	ASTM D 790
	Modulus (ksi)	502	
	Offset Yield (ksi)	14.8	
	Strain (%)	5.7	

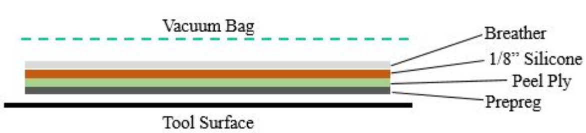
T700S/G83C Mechanical Properties (Cured at 150°C)

Room Temp:

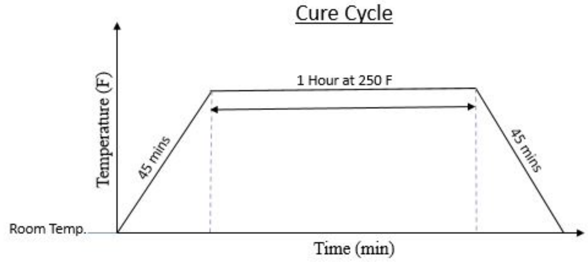
0° Tensile Strength*	425 ksi	ASTM D3039
0° Tensile Modulus*	19.3 msi	ASTM D3039
0° Tensile Strain	2.0 %	ASTM D3039
0° Comp. Strength*	221 ksi	ASTM D695
90° Tensile Strength	8.8 ksi	ASTM D3039
ILSS	12.8 ksi	ASTM D2344
+/- 45° In Plane Shear Strength	17.1 ksi	ASTM D3518

*Normalized to Vf=60%

Layup



Cure Cycle



MSEG 410/610
Experimental Mechanics of Composite Materials

Laboratory Report Format
(General Guidelines)

I. Title Page
- **A. Title of Lab**
- **B. Author**
- **C. Group Members**
- **D. Date Performed**
- **E. Date Submitted**

II. Abstract
- **A. Objective**
- **B. Summary of Results**

III. Procedure
- **A. ASTM Standard**
- **B. Specimen Lay-up and Geometries**
- **C. Instrumentation**
- **D. Instron Settings**
- **E. Testing Environment**
- **F. Specimen Dimensions**

IV. Results
- **A. Data Reduction Scheme**
- **B. Tables**
    - **1. Specimen Geometry**
    - **2. Stress-strain data**
- **C. Graphs of Stress-strain data**
- **D. Summary of Test Results**
    - **1. Average value**
    - **2. Standard deviation**
- **E. Description of Failure Modes**

V. Error Analysis

VI. Theoretical Predictions (as required)

VII. Correlation of Theory and Experiments (as required)

VIII. Conclusions

IX. Appendices
- **A. Sample Calculations**
    - **1. Properties**
    - **2. Error Analysis**
- **B. HW (as required)**
- **C. Fabrication and Processing (as required)**

***** Report results in SI units with English units in parenthesis (optional).

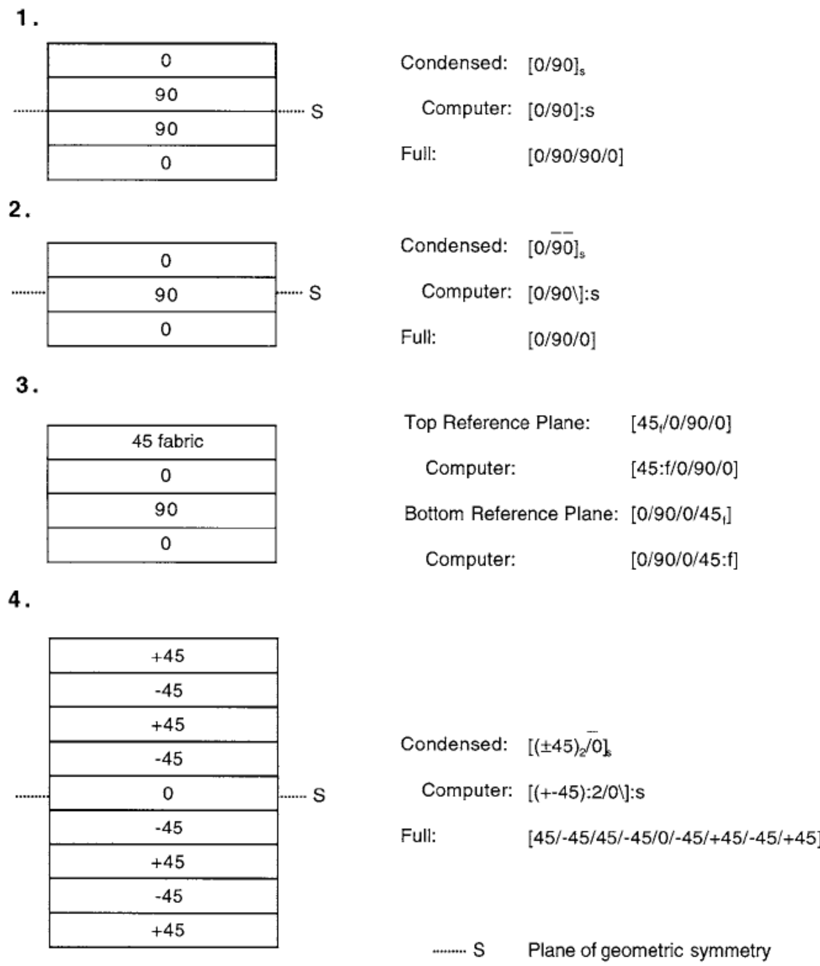
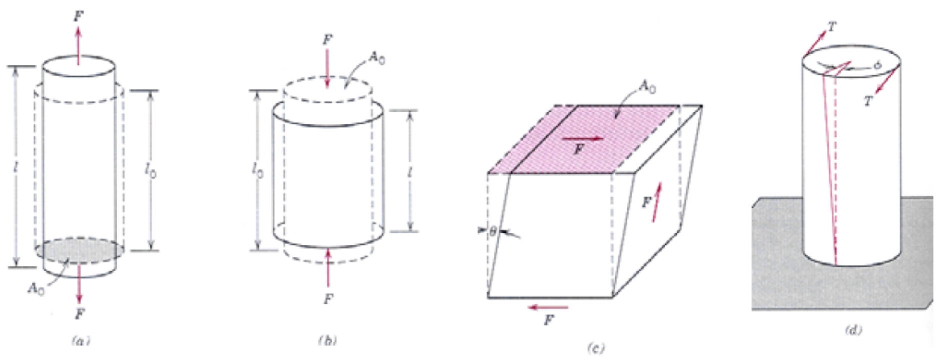


FIG. 1 Examples of Laminate Orientation Code

Concepts of stress and strain

- Tension, compression, shear, and torsion



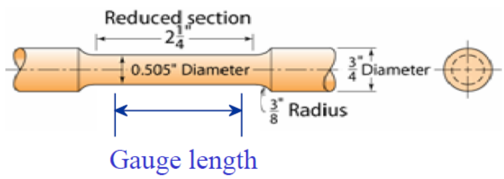
Stress-strain testing

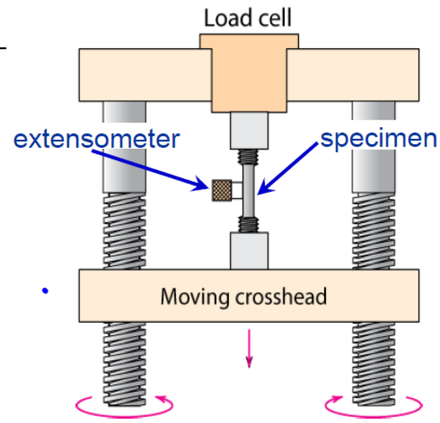
- Tension tests
  - engineering stress

$$\sigma = \frac{F}{A_0}$$

  - engineering strain

$$\varepsilon = \frac{l_i - l_0}{l_0} = \frac{\Delta l}{l_0}$$

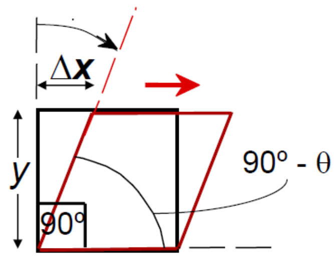


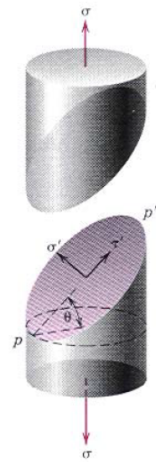


- Compression tests

Shear stress

- Shear and torsional tests
  - Shear stress $$\tau = \frac{F}{A_0} = G\gamma$$
  - Shear strain $$\gamma = \Delta x / y = \tan\theta$$



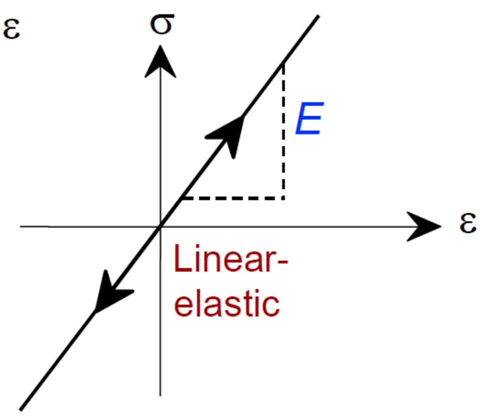


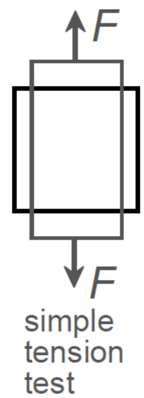
- Geometric considerations of the stress state

Linear elastic properties

- Modulus of Elasticity, *E*:
  (also known as Young's modulus)
- Hooke's Law:

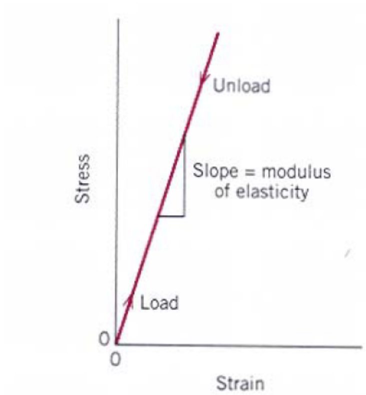
$$\sigma = E\,\varepsilon$$

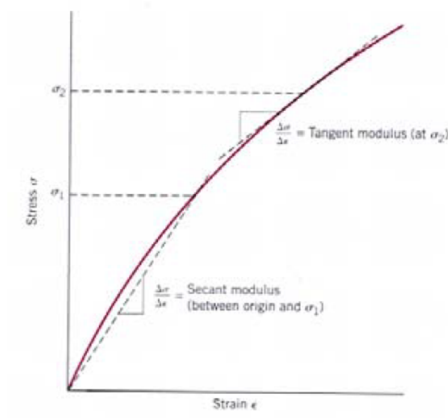


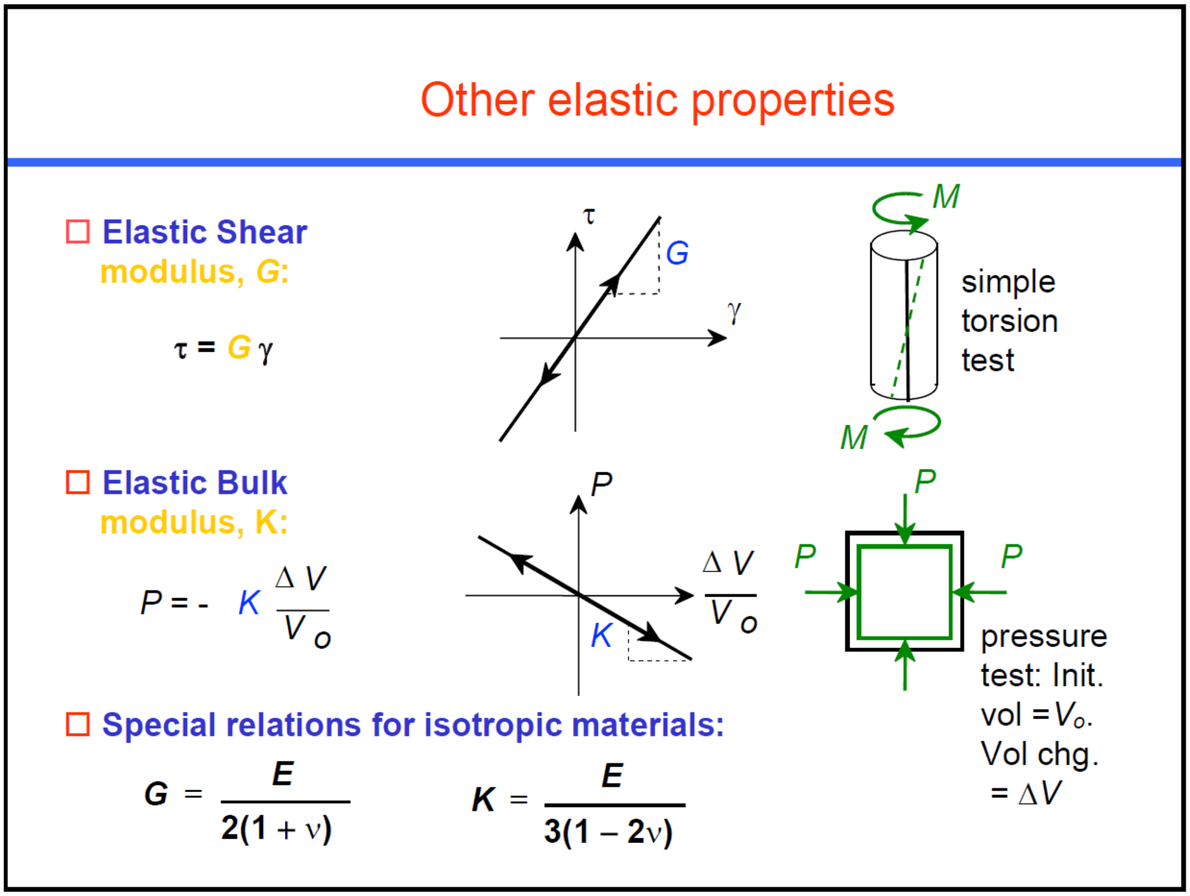


Stress-strain behavior

- Stress-strain for linear elastic deformation
- Stress-strain for non-linear elastic deformation







Resin is isotropic; Fiber is transversely isotropic; Composite is transversely isotropic. Special relationship holds only for resin.

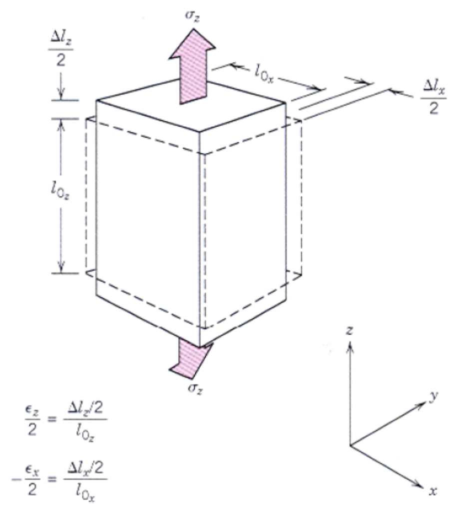
Elastic properties of materials

- Poisson's ratio

$$\nu = -\frac{\varepsilon_x}{\varepsilon_z} = -\frac{\varepsilon_y}{\varepsilon_z}$$

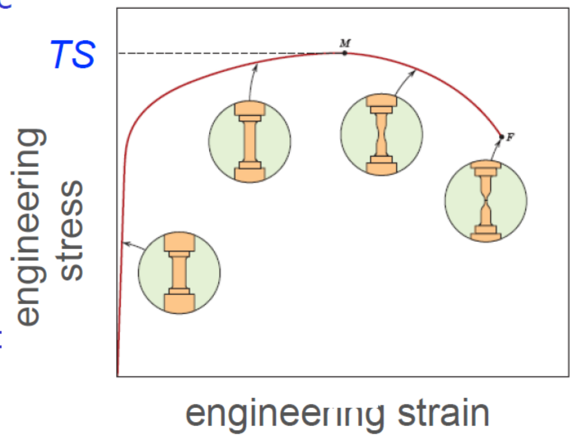
metals: ν ~ 0.33
ceramics: ν ~ 0.25
polymers: ν ~ 0.40

Units:
E: [GPa] or [psi]
ν: dimensionless



Tensile strength

- Tensile strength: the stress at the maximum on the engineering stress-strain curve
- Metals: occurs when noticeable "necking" starts
- Ceramics: occurs when crack propagation starts
- Polymers: occurs when polymer backbones are aligned and about to break

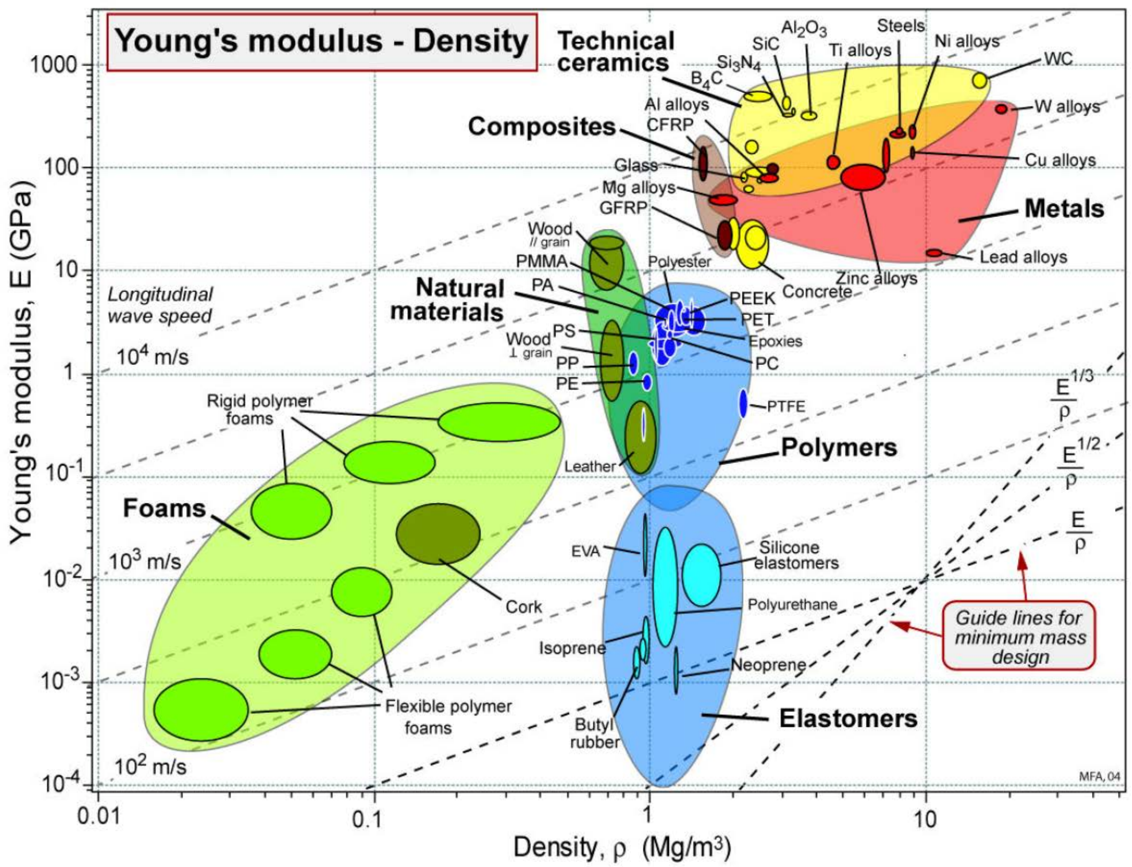


Composites are Anisotropic: Properties are dependent on direction of loading.

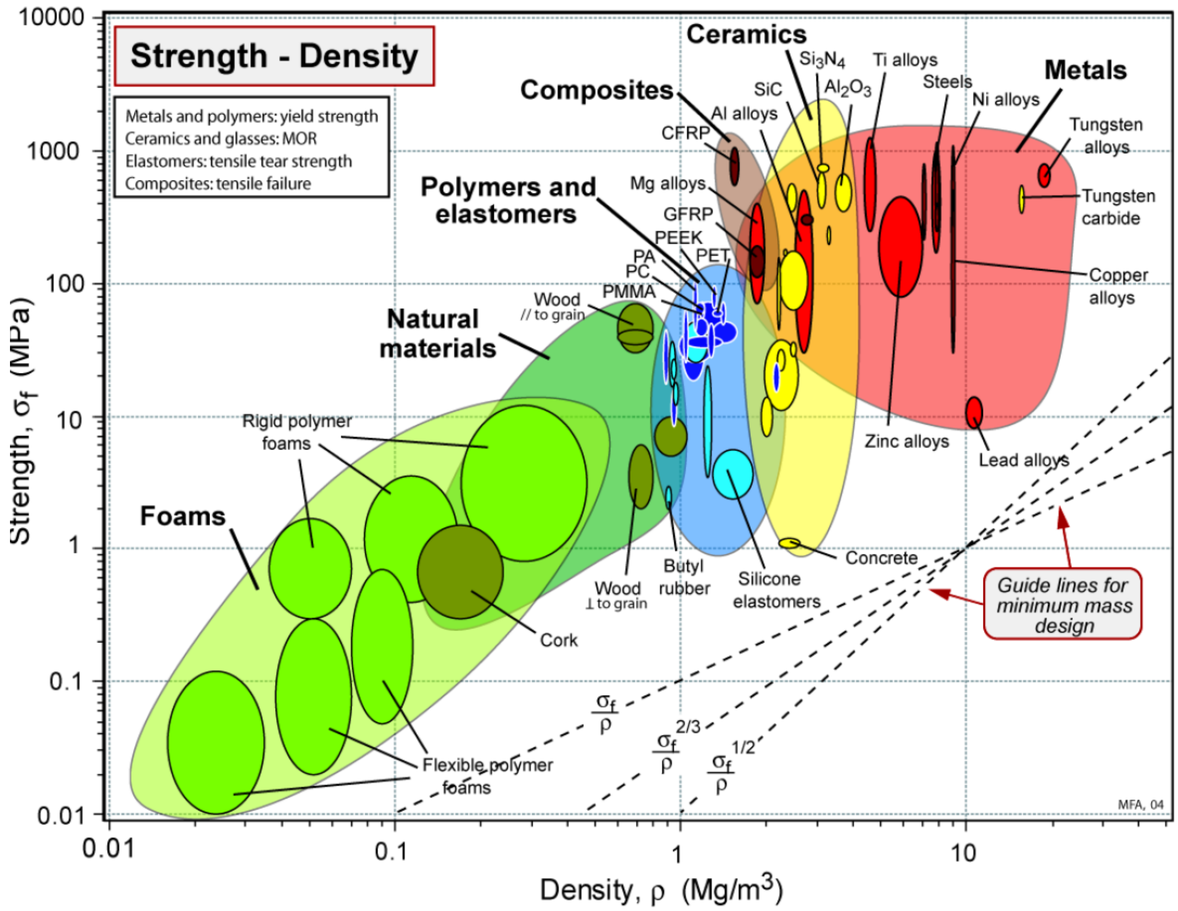
Continuous Fiber Micromechanics

Fiber Properties (Transversely Isotropic)	Values	Units	**Matrix Properties (Isotropic)**	Values	Units
AS4 Graphite			**PEEK**		
Longitudinal Modulus, E1f	3.20E+07	psi	Modulus, Em	1.37E+06	psi
Transverse Modulus, E2f	1.45E+06	psi	Poisson's Ratio, Num	0.300	
Long-Trans Shear Modulus, G12f	7.00E+05	psi	Thermal Exp. Coef., CTE, Al	1.50E-05	1/F
Trans-Normal Poisson's Ratio, Nu23f	0.450				
Long-Trans Poisson's Ratio, Nu12f	0.320		***Shear Modulus, Gm***	***5.27E+05***	***psi***
Longitudinal CTE, Alpha1f	0.00E+00	1/F			
Transverse CTE, Alpha2f	5.00E-06	1/F			
			Fiber Volume Fraction, Vf	60%	
Normal Modulus, E3f	***1.45E+06***	***psi***	(Less than 1.0)		
Trans-Normal Shear Modulus, G2	***5.00E+05***	***psi***	***Resin Volume Fraction, V***	***40%***	
Long-Normal Shear Modulus, G13	***7.00E+05***	***psi***			
Long-Normal Poisson's Ratio, Nu1	***0.320***				
Normal CTE, Alpha3f	***5.00E-06***	***1/F***			

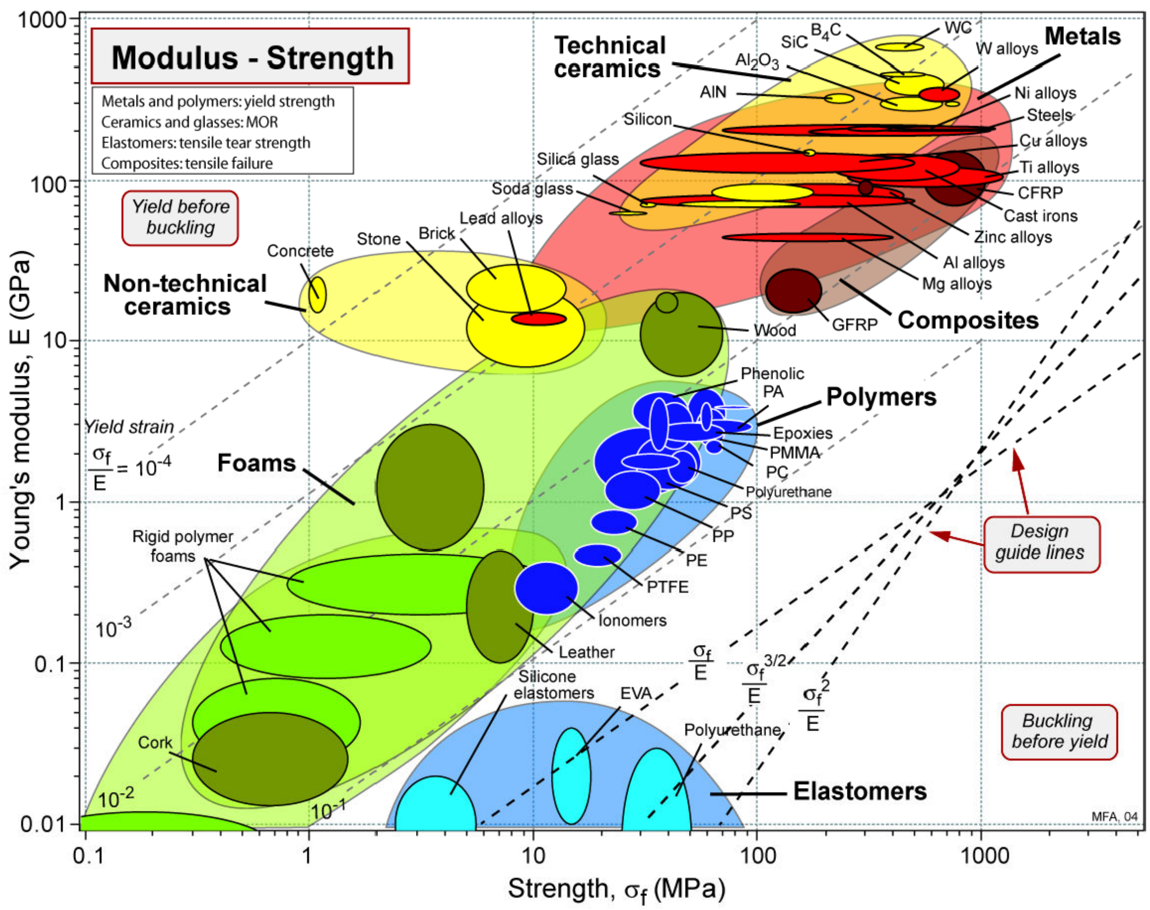
Predicted Lamina Properties					
Longitudinal Modulus, E1	1.975E+07	psi	Longitudinal CTE, Alpha1	4.109E-07	1/F
Transverse Modulus, E2	1.465E+06	psi	Transverse CTE, Alpha2	1.065E-05	1/F
Normal Modulus, E3	1.465E+06	psi	Normal CTE, Alpha3	1.065E-05	1/F
Trans-Normal Shear Modulus, G23	5.106E+05	psi			
Long-Normal Shear Modulus, G13	6.244E+05	psi			
Long-Trans Shear Modulus, G12	6.244E+05	psi			
Trans-Normal Poisson's Ratio, Nu23	0.4352				
Long-Normal Poisson's Ratio, Nu13	0.3120				
Long-Trans Poisson's Ratio, Nu12	0.3120				



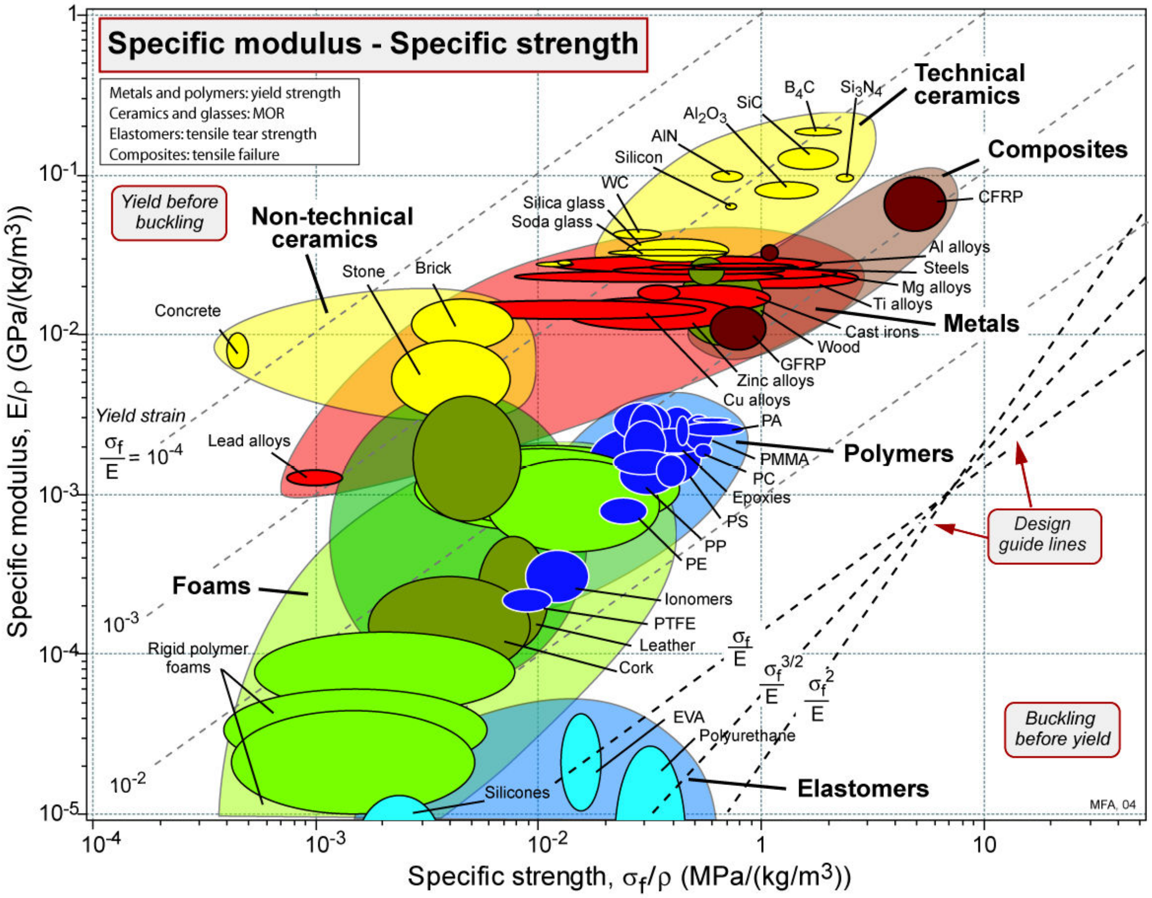
Young's modulus - Density
Technical ceramics
Composites
Natural materials
Foams
Polymers
Elastomers
Metals
Longitudinal wave speed
10^4 m/s
10^3 m/s
10^2 m/s
Young's modulus, E (GPa)
Density, ρ (Mg/m³)
Guide lines for minimum mass design
$\frac{E^{1/3}}{\rho}$
$\frac{E^{1/2}}{\rho}$
$\frac{E}{\rho}$
MFA, 04



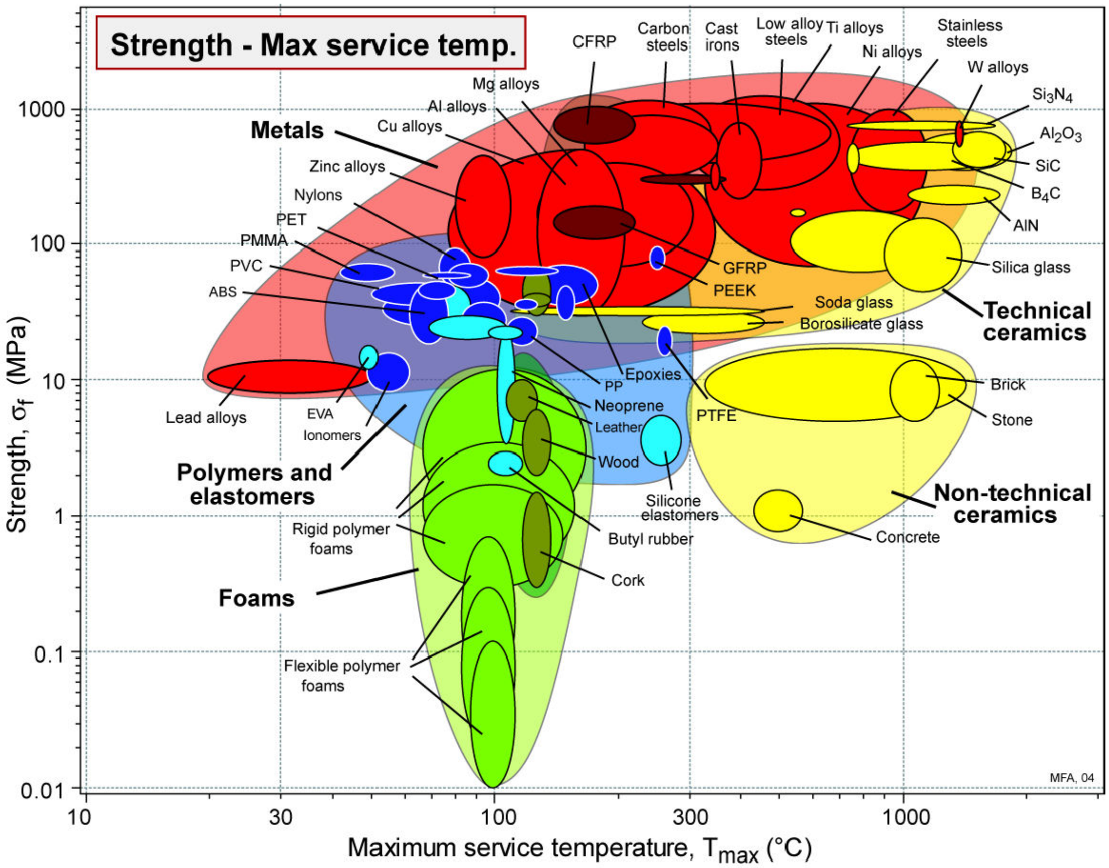
Strength - Density
Metals and polymers: yield strength
Ceramics and glasses: MOR
Elastomers: tensile tear strength
Composites: tensile failure
Ceramics
Composites
Metals
Polymers and elastomers
Natural materials
Foams
Si3N4
SiC
Al2O3
Ti alloys
Steels
Ni alloys
Al alloys
CFRP
Tungsten alloys
Tungsten carbide
Mg alloys
GFRP
PEEK
PET
PA
PC
PMMA
Wood // to grain
Copper alloys
Rigid polymer foams
Zinc alloys
Lead alloys
Concrete
Butyl rubber
Silicone elastomers
Wood ⊥ to grain
Cork
Guide lines for minimum mass design
Flexible polymer foams
σf/ρ
σf^2/3/ρ
σf^1/2/ρ
MFA, 04
Strength, σf (MPa)
Density, ρ (Mg/m3)
10000
1000
100
10
1
0.1
0.01
0.01
0.1
1
10



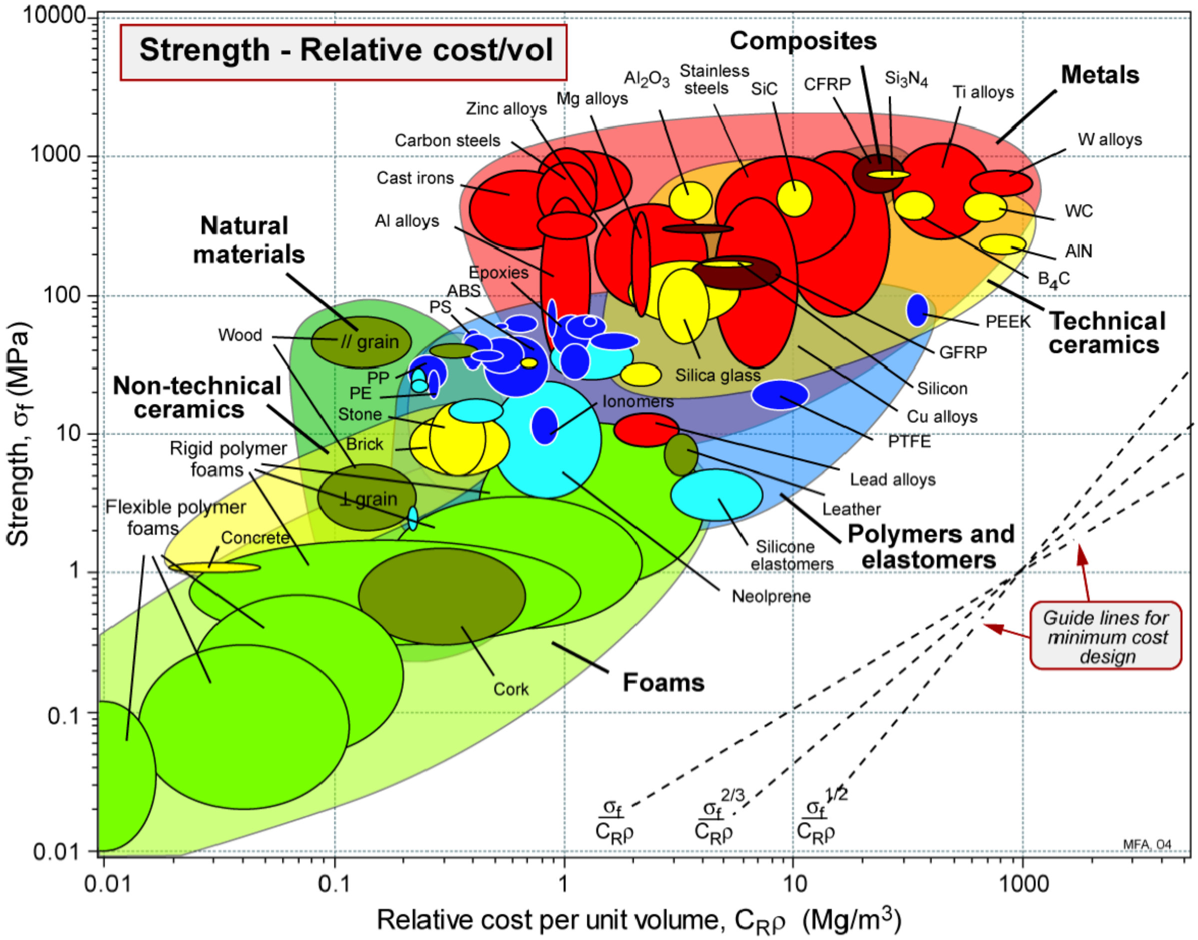
Modulus - Strength
Metals and polymers: yield strength
Ceramics and glasses: MOR
Elastomers: tensile tear strength
Composites: tensile failure
Yield before buckling
Technical ceramics
Metals
WC
B_4C
SiC
Al_2O_3
AlN
W alloys
Ni alloys
Steels
Cu alloys
Ti alloys
CFRP
Cast irons
Zinc alloys
Al alloys
Mg alloys
GFRP
Composites
Silicon
Silica glass
Soda glass
Lead alloys
Brick
Stone
Concrete
Non-technical ceramics
Wood
Phenolic
PA
Polymers
Epoxies
PMMA
PC
Polyurethane
PS
PP
PE
PTFE
Ionomers
Leather
Foams
Rigid polymer foams
Cork
Yield strain
$\frac{\sigma_f}{E} = 10^{-4}$
10^{-3}
10^{-2}
10^{-1}
Design guide lines
Buckling before yield
$\frac{\sigma_f}{E}$
$\frac{\sigma_f^{3/2}}{E}$
$\frac{\sigma_f^2}{E}$
Silicone elastomers
EVA
Polyurethane
Elastomers
MFA, 04
Young's modulus, E (GPa)
Strength, σ_f (MPa)
1000
100
10
1
0.1
0.01
0.1
1
10
100
1000



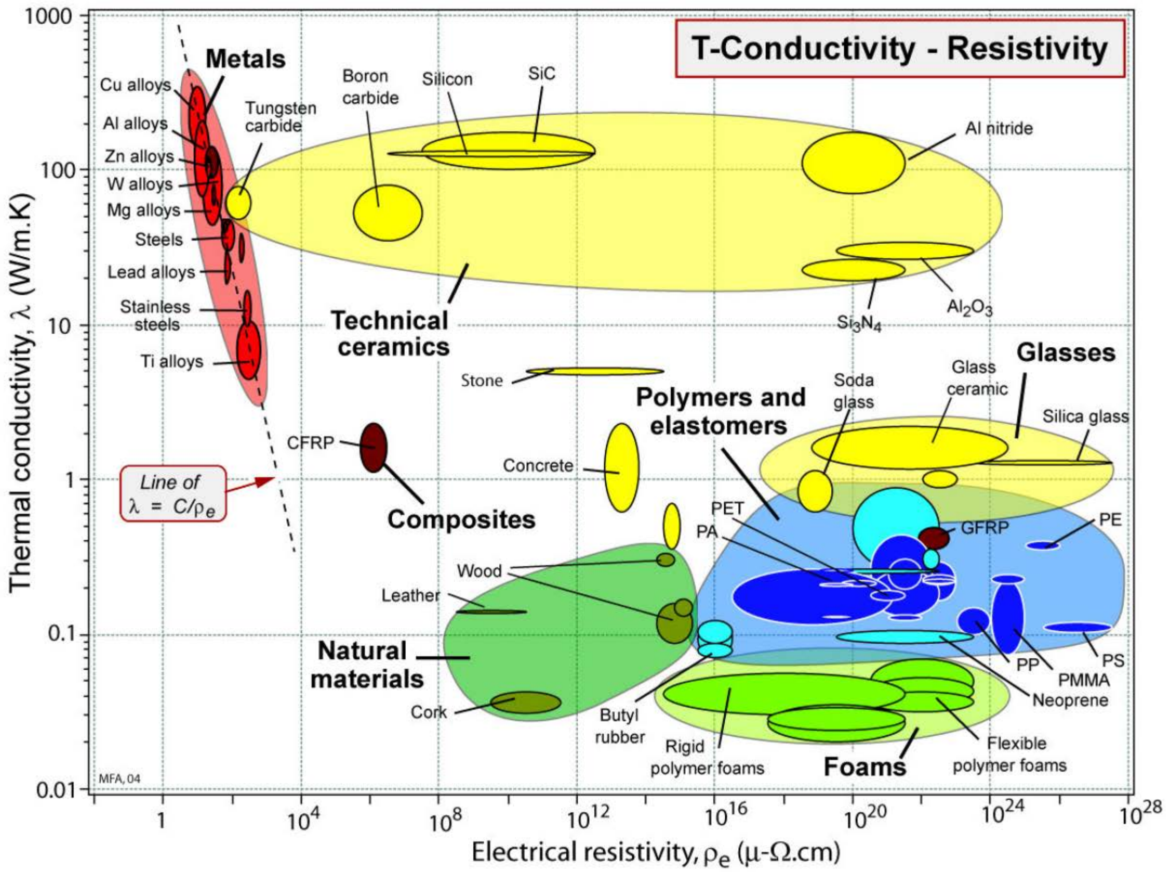
Specific modulus - Specific strength
Metals and polymers: yield strength
Ceramics and glasses: MOR
Elastomers: tensile tear strength
Composites: tensile failure
Yield before buckling
Buckling before yield
Design guide lines
Technical ceramics
Composites
Non-technical ceramics
Metals
Polymers
Foams
Elastomers
Yield strain
$\frac{\sigma_f}{E} = 10^{-4}$
10^{-3}
10^{-2}
$\frac{\sigma_f}{E}$
$\frac{\sigma_f^{3/2}}{E}$
$\frac{\sigma_f^{2}}{E}$
B_4C
Si_3N_4
SiC
Al_2O_3
AlN
Silicon
WC
Silica glass
Soda glass
CFRP
Al alloys
Steels
Mg alloys
Ti alloys
Cast irons
Wood
GFRP
Zinc alloys
Cu alloys
Concrete
Stone
Brick
Lead alloys
PA
PMMA
PC
Epoxies
PS
PP
PE
Ionomers
PTFE
Leather
Cork
Rigid polymer foams
EVA
Polyurethane
Silicones
MFA, 04
Specific modulus, E/ρ (GPa/(kg/m^3))
Specific strength, σ_f/ρ (MPa/(kg/m^3))
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
1
10



Strength - Max service temp.
Metals
Polymers and elastomers
Foams
Technical ceramics
Non-technical ceramics
CFRP
Carbon steels
Cast irons
Low alloy steels
Ti alloys
Ni alloys
Stainless steels
W alloys
Si_3N_4
Al_2O_3
SiC
B_4C
AlN
Silica glass
Mg alloys
Al alloys
Cu alloys
Zinc alloys
Nylons
PET
PMMA
PVC
ABS
GFRP
PEEK
Soda glass
Borosilicate glass
Epoxies
PP
Neoprene
Leather
Wood
PTFE
Brick
Stone
Lead alloys
EVA
Ionomers
Silicone elastomers
Butyl rubber
Rigid polymer foams
Concrete
Cork
Flexible polymer foams
MFA, 04
Strength, σ_f (MPa)
Maximum service temperature, T_{max} (°C)
0.01
0.1
1
10
100
1000
10
30
100
300
1000



Strength - Relative cost/vol
Composites
Metals
Technical ceramics
Natural materials
Non-technical ceramics
Polymers and elastomers
Foams
Al2O3
Stainless steels
SiC
CFRP
Si3N4
Ti alloys
W alloys
WC
AlN
B4C
PEEK
GFRP
Silicon
Cu alloys
PTFE
Lead alloys
Leather
Silicone elastomers
Neoprene
Cork
Zinc alloys
Mg alloys
Carbon steels
Cast irons
Al alloys
Epoxies
ABS
PS
PP
PE
Stone
Brick
Wood
// grain
⊥ grain
Rigid polymer foams
Flexible polymer foams
Concrete
Silica glass
Ionomers
Guide lines for minimum cost design
σf/CRρ
σf^2/3/CRρ
σf^1/2/CRρ
MFA, 04
Strength, σf (MPa)
Relative cost per unit volume, CRρ (Mg/m3)
10000
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
1000


T-Conductivity - Resistivity
Metals
Cu alloys
Al alloys
Zn alloys
W alloys
Mg alloys
Steels
Lead alloys
Stainless steels
Ti alloys
Tungsten carbide
Boron carbide
Silicon
SiC
Al nitride
Technical ceramics
Si_3N_4
Al_2O_3
Stone
Glasses
Glass ceramic
Soda glass
Silica glass
Polymers and elastomers
CFRP
Line of $\lambda = C/\rho_e$
Composites
Concrete
PET
PA
GFRP
PE
Wood
Leather
Natural materials
Cork
Butyl rubber
Rigid polymer foams
Foams
Flexible polymer foams
PP
PMMA
PS
Neoprene
MFA, 04
Thermal conductivity, λ (W/m.K)
Electrical resistivity, ρ_e (μ-Ω.cm)
1000
100
10
1
0.1
0.01
1
10^4
10^8
10^{12}
10^{16}
10^{20}
10^{24}
10^{28}