

Metody a normy pro zkoušení kompozitních materiálů

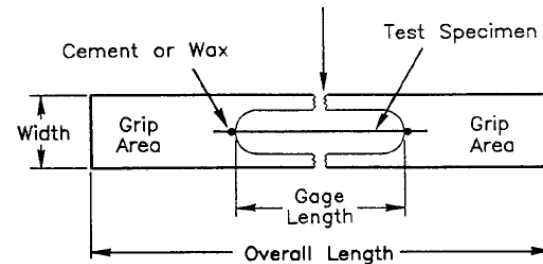
Karel Doubrava

ČVUT v Praze, Fakulta strojní

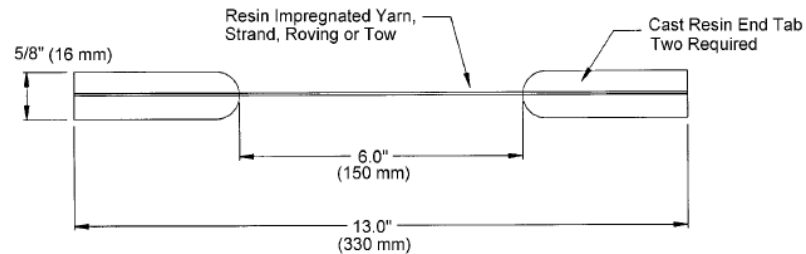
- Zkoušení laminátů
 - Vlákna, Matrice, Laminy, Lamináty
- Zkoušení sendvičů
- Odporová tenzometrie na kompozitních konstrukcích

Vlákna

- ASTM D 3379



- [ASTM D 4018](#)



- Zkouška jednosměr. laminátu

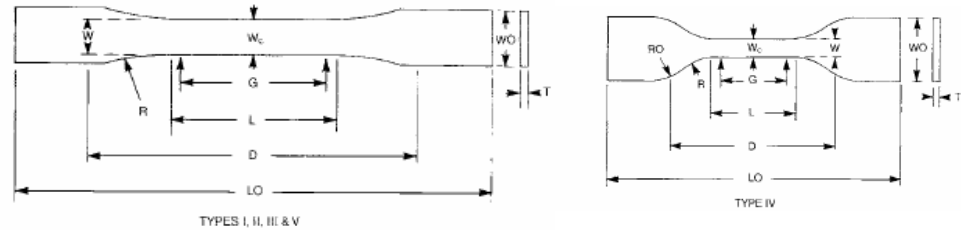
[ASTM D 3039](#)

$$Vlastnost_f [\%] = \frac{Vlastnost_{0^\circ} \cdot 100}{V_f}$$

Matrice

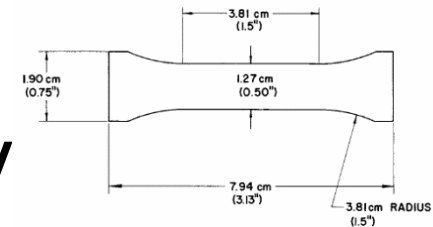
- Tah [ASTM D 638](#)

$$F_m^{tu}, F_m^{ty}, E_m^t, \nu_m^t, \epsilon_m^{tu}$$



- Tlak [D 695](#) $F_m^{cu}, F_m^{cy}, E_m^c, \nu_m^c, \epsilon_m^{cu}$

(prizma, válce, tenké v



- Smyk ASTM E 143, [ASTM D 5379](#)

$$F_m^{su}, F_m^{sy}, G_m^s$$

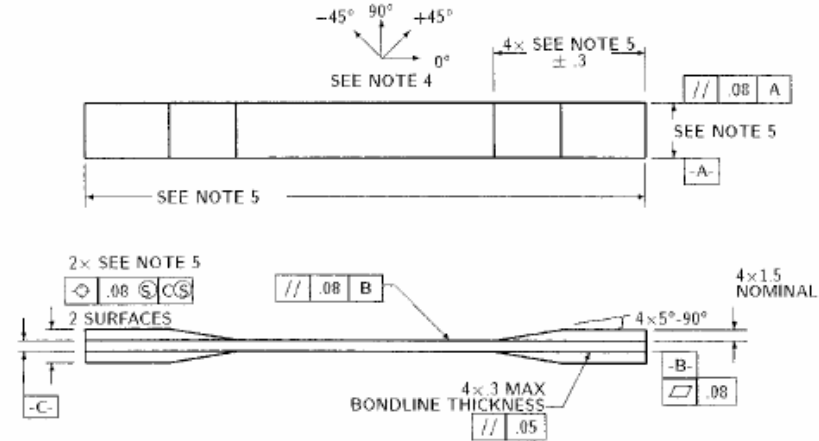
Druhy zkoušek – laminy, lamináty

- Tah ([ASTM D 3039](#))
- Tlak ([ASTM D 3410](#), [ASTM D 695](#))
- Smyk ([ASTM D 3518](#), [D 5379](#), ...)
- Interlaminární smyk ([ASTM D 2344](#))

Tahová zkouška

ASTM D 3039

- Pevnost v tahu
- Modul pružnosti
- Poissonovo číslo

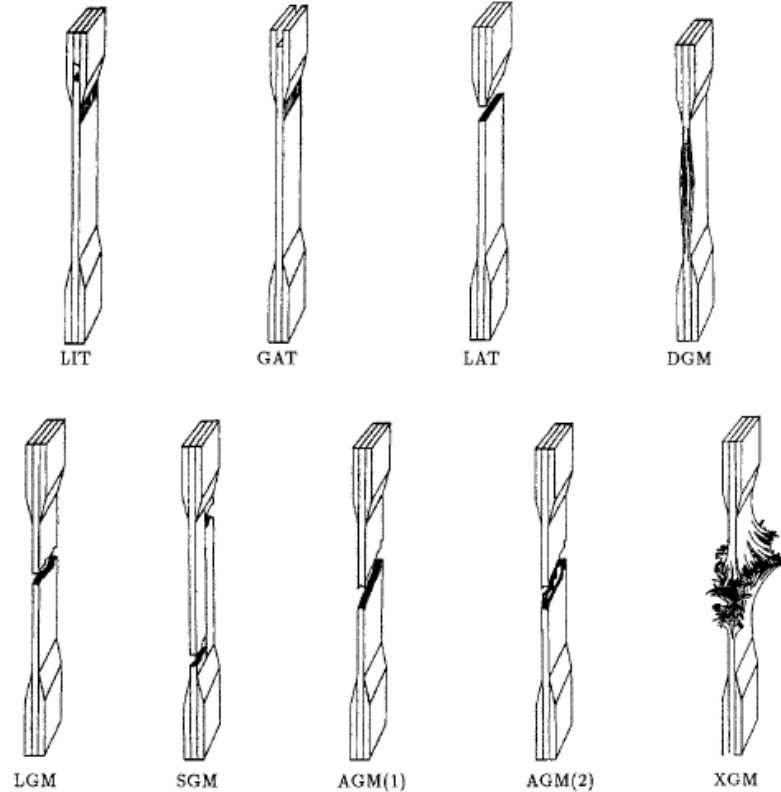


$$E_1 = \frac{\sigma_1^b - \sigma_1^a}{\varepsilon_1^b - \varepsilon_1^a}$$

$a \dots 0,1\%$, $b \dots 0,3\%$

ASTM D 3039 klasifikace poruch

1. znak	2. znak	3. znak	
Mód poruchy	Plocha poruchy	Místo poruchy	
Angled edge Delamination	A Inside grip/tab D At grip/tab	I Bottom A Top	B T
Grip/tab	G <1Wfrom grip/tab	A Left	L
Lateral	L Gage	G Right	R
Multi—mode long.-Splitting	M Multiple areas S Various	M Middle V Various	M V
eXplosive	X Unknown	U Unknown	U
Other	O		



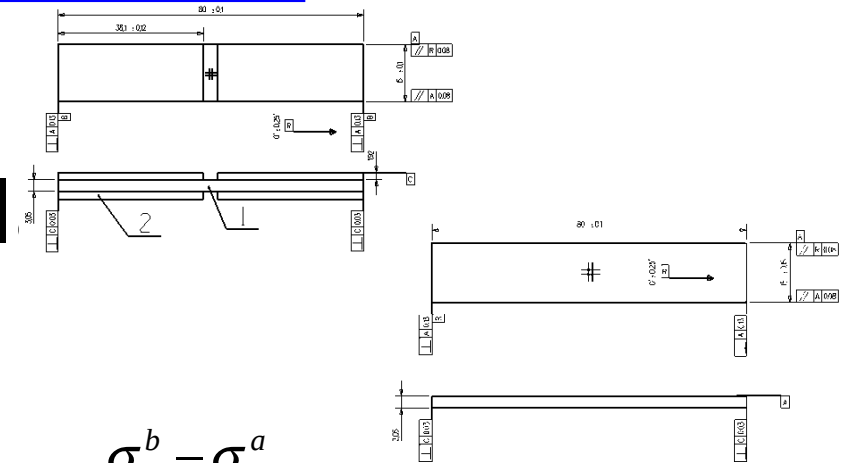
Tlakové zkoušky

- ASTM D-695 (SACMA SRM-1)
- ASTM D 3410 (Celanese, IITRI)
- ASTM D 5467

Tlakové zkoušky

ASTM D-695

- Pevnost v tlaku
- Modul pružnosti v tlaku



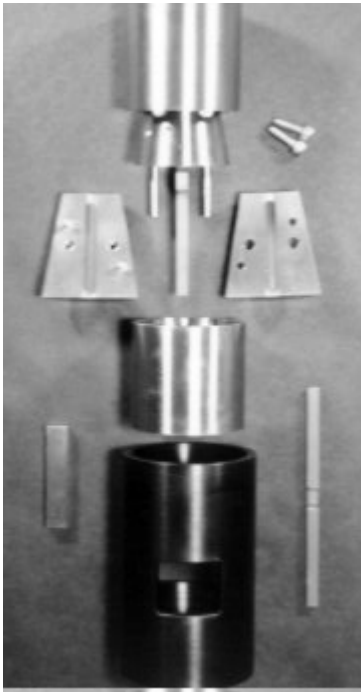
<http://www.wyomingtestfixtures.com/>

$$E_1 = \frac{\sigma_1^b - \sigma_1^a}{\epsilon_1^b - \epsilon_1^a}$$

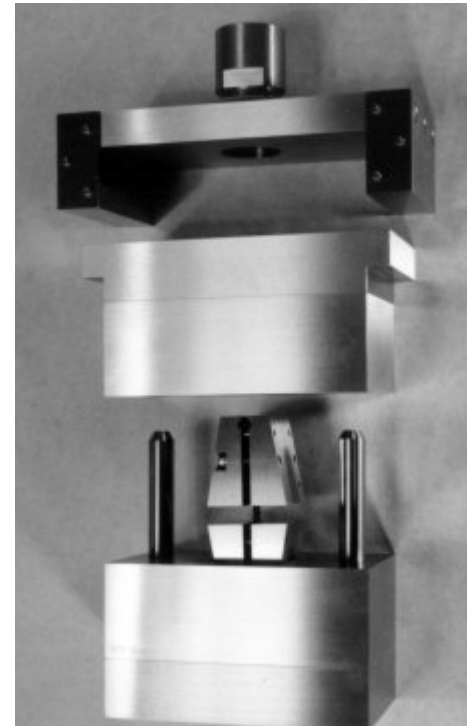
Tlakové zkoušky

ASTM D 3410

Celanese



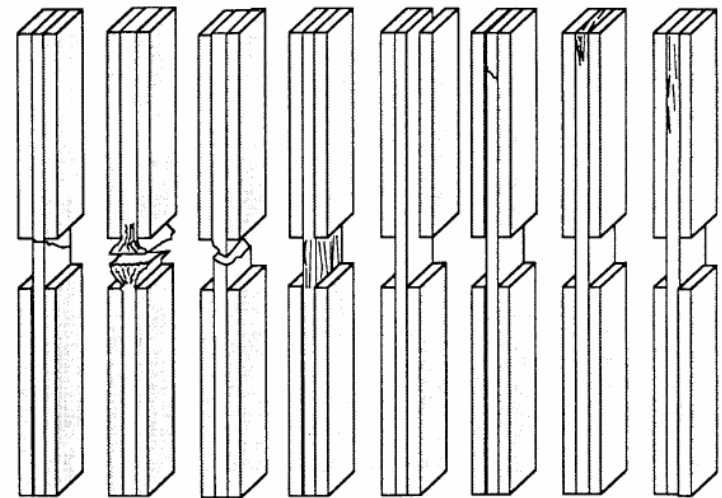
IITRI



<http://www.wyomingtestfixtures.com/>

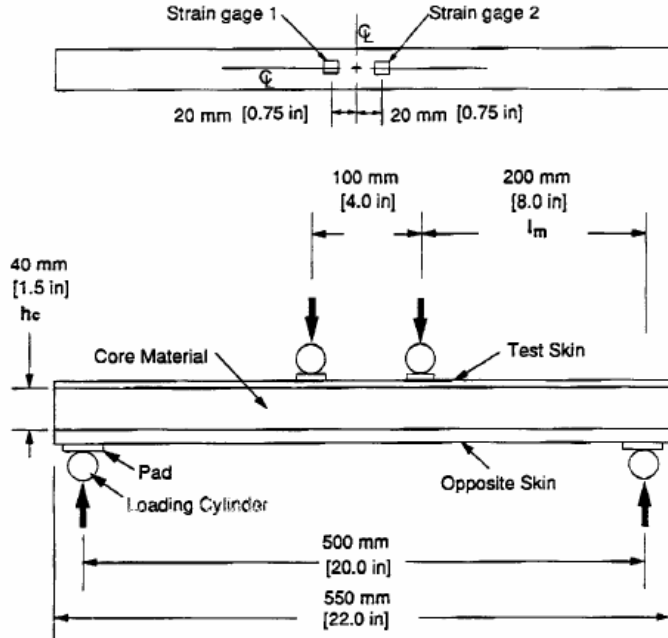
ASTM D 3410 klasifikace poruch

1. znak	2. znak	3. znak
Mód poruchy	Plocha poruchy	Místo poruchy
Angled	A Inside grip/tab	Bottom B
Brooming	B At grip/tab	A Top T
end-Crushing	C Gage	G Left L
Delamination	D Multiple areas	M Right R
Euler bucling	E Tab adhesive	T Middle M
tHrough-thickness	H Various	V Various V
Kink bands	K Unknown	U Unknown U
Lateral	L	
Multi—mode	M	
long.-Splitting	S	
Transverse shear	T	
eXplosive	X	
Other	O	



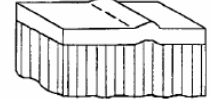
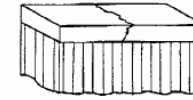
TAT BGM HAT SGV DTT HIT CIT DIT
 Acceptable Failure Modes and Areas Unacceptable Failure Modes and Areas

ASTM D 5467



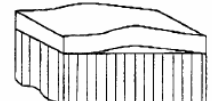
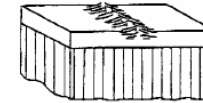
Acceptable

Not Acceptable



HGM

WGM



FGM

DGM



CGM

1. znak	2. znak	3. znak
Mód poruchy	Plocha poruchy	Místo poruchy
skin to core Delamination	D At load cylinder	A Left
Filament fracture	F Gage	G Right
through-thickness Layer instability	H Multiple areas	M Middle
local Wrinkling	L Outside gage	O Various
Multi-mode	W Various	V Unknown
core Crushing	M Unknown	U

long.-Splitting	S
transverse shear	T
explosive	X
Other	O

$a \dots 0,1\%, b \dots 0,3\%$

$$F^{cu} = \frac{P^{\max} l_m \left(a - \bar{y} + \frac{h_f}{2} \right)}{2w \left[h_f (a - \bar{y})^2 + \frac{E_0}{E_f} h_a \bar{y}^2 \right]}$$

$$\sigma^c = \frac{P l_m \left(a - \bar{y} + \frac{h_f}{2} \right)}{2w \left[h_f (a - \bar{y})^2 + \frac{E_0}{E_f} h_a \bar{y}^2 \right]}$$

$$E = \frac{\sigma^b - \sigma^a}{\varepsilon^b - \varepsilon^a}$$

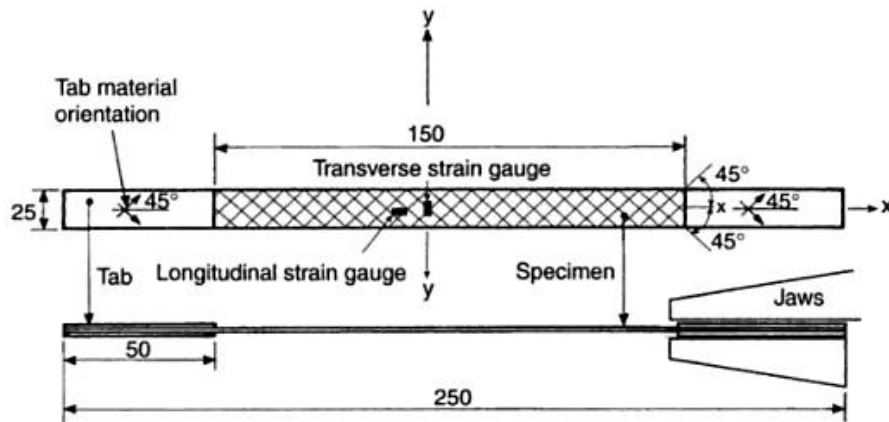
Smykové zkoušky

- Jednoosý tah $\pm 45^\circ$ laminátu
- Smykové testy s dvojitým a trojitým vedením
- Smykový vzorek s V vrubem (Iosipescu, s vedením)
- Krut tenkostěnné trubky

Smyk - Jednoosý tah $\pm 45^\circ$ laminátu

- BS EN ISO 14,129, [ASTM D 3518](#)
- Vzorek vrstva $>0,125$ mm, 16 vrstev

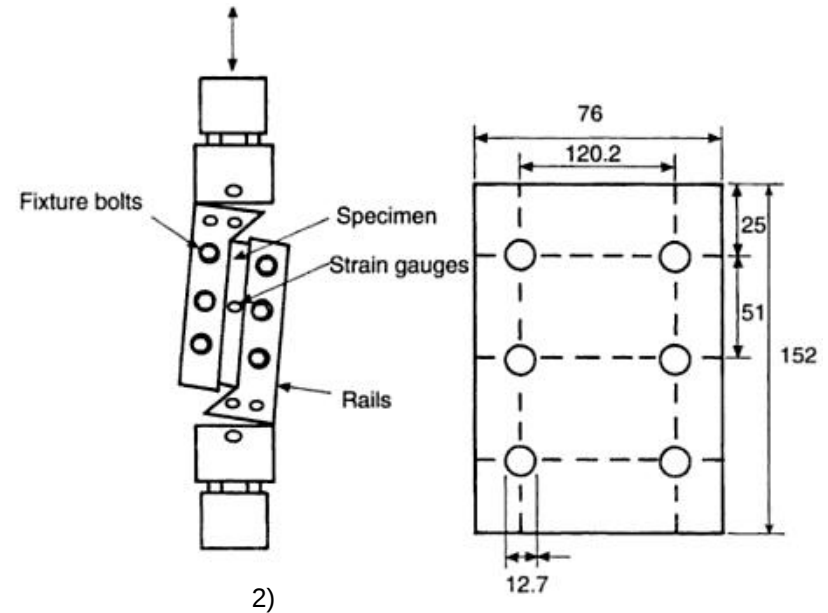
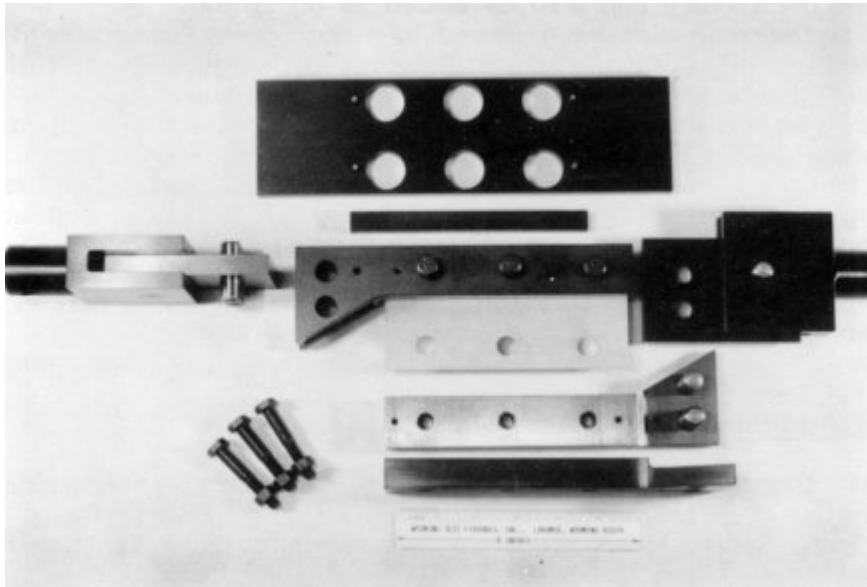
$$\sigma_{11} = \frac{\sigma_{xx}}{2} + \tau_{xy}; \quad \sigma_{22} = \frac{\sigma_{xx}}{2} - \tau_{xy}; \quad \tau_{12} = \pm \tau_{xy} \quad \varepsilon_{11} = \varepsilon_{22} = \frac{\varepsilon_{xx} + \varepsilon_{yy}}{2}; \quad \gamma_{12} = \varepsilon_{xx} - \varepsilon_{yy}$$



$$G_{12} = \frac{\sigma_{xx}}{2(\varepsilon_{xx} - \varepsilon_{yy})} = \frac{\tau_{12}^b - \tau_{12}^a}{\gamma_{12}^b - \gamma_{12}^a}$$

$$S_{12} = \frac{P_{\max}}{2bh}$$

Smykové testy s dvojitým vedením ASTM D 4255



<http://www.wyomingtestfixtures.com/>

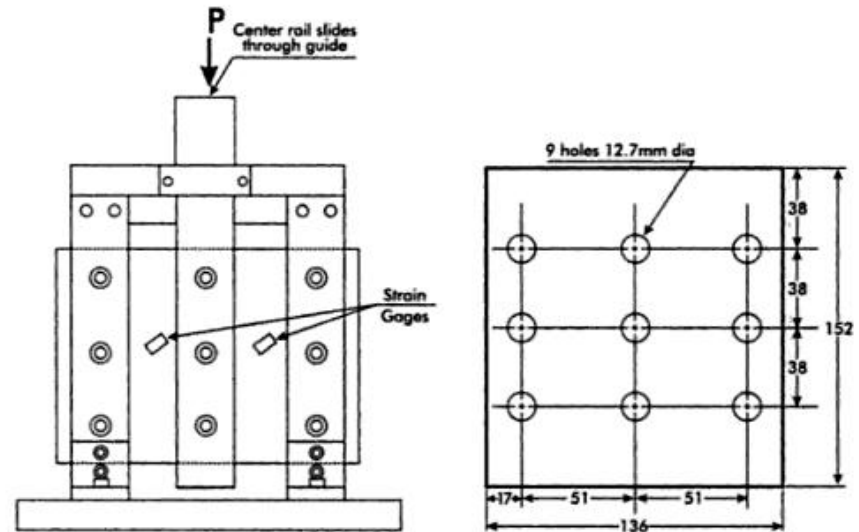
$$S_{xy} = \frac{P_{\max}}{Lh}$$

$$G_{12} = \frac{\Delta\tau_{xy}}{\Delta\gamma_{xy}} = \frac{\Delta P}{2Lh\Delta\varepsilon_{45}}$$

Smykové testy s trojitým vedením ASTM D 4255



<http://www.wyomingtestfixtures.com/>



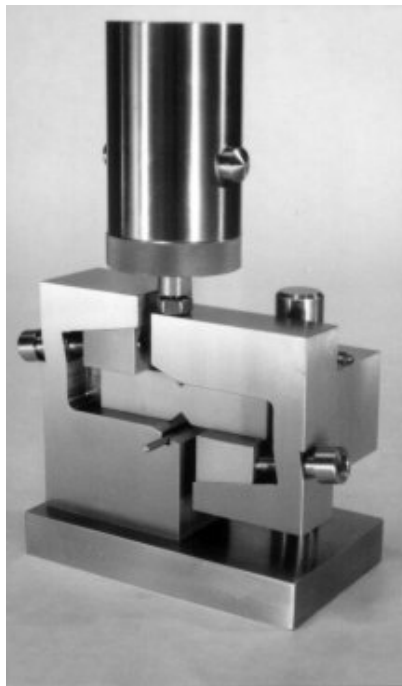
3)

$$S_{xy} = \frac{P_{\max}}{2Lh}$$

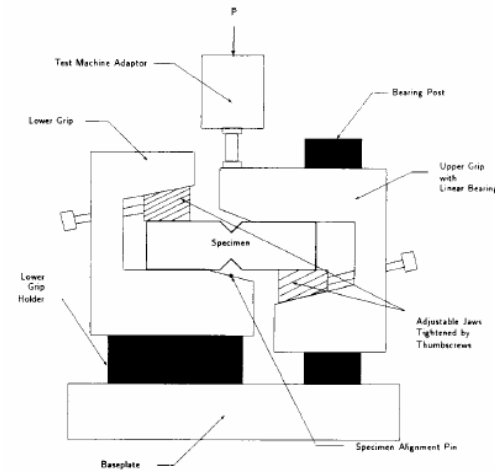
$$G_{12} = \frac{\Delta\tau_{xy}}{\Delta\gamma_{xy}} = \frac{\Delta P}{4Lh\Delta\varepsilon_{45}}$$

Smyk -- Smykový vzorek s V vrubem (Iosipescu)

ASTM D 5379



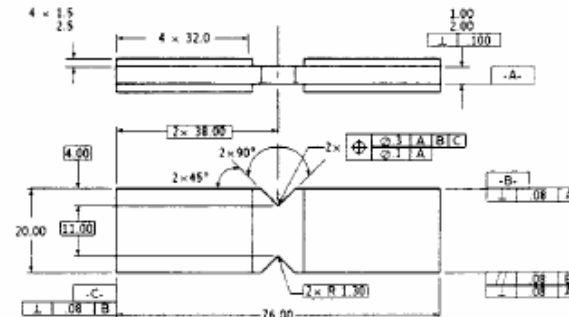
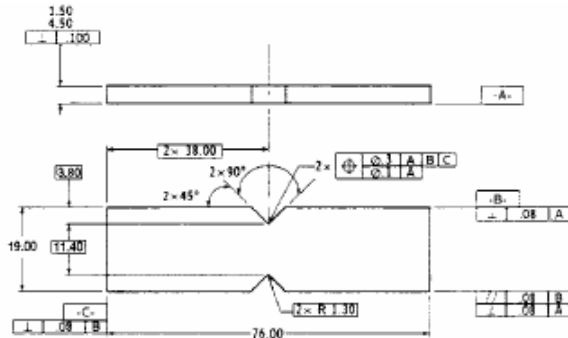
<http://www.wyomingtestfixtures.com/>



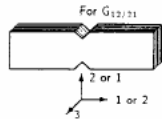
$$F^u = \frac{P^u}{w \cdot h}, \tau_i = \frac{P_i}{w \cdot h}$$

$$\gamma = \left| \varepsilon_{45^\circ} \right| + \left| \varepsilon_{-45^\circ} \right| \quad G = \frac{\Delta \tau}{\Delta \gamma}$$

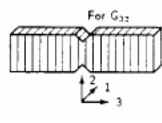
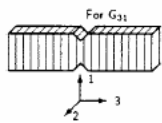
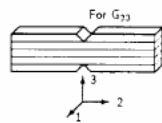
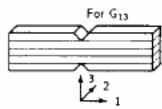
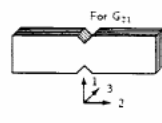
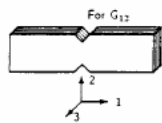
ASTM D 5379



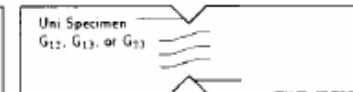
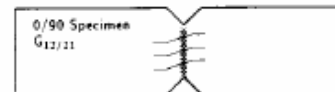
[0/90]_ns or [90/0]_ns Laminates



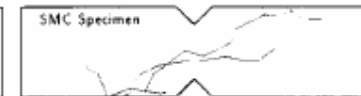
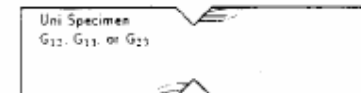
Unidirectional Laminates



Typical Acceptable Failure Modes

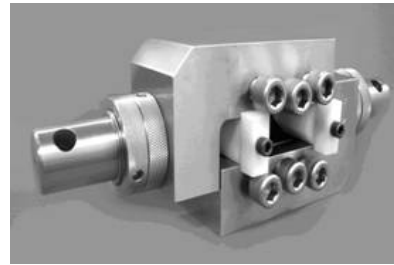
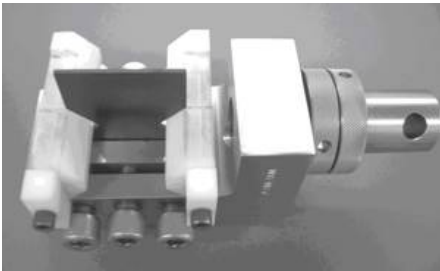
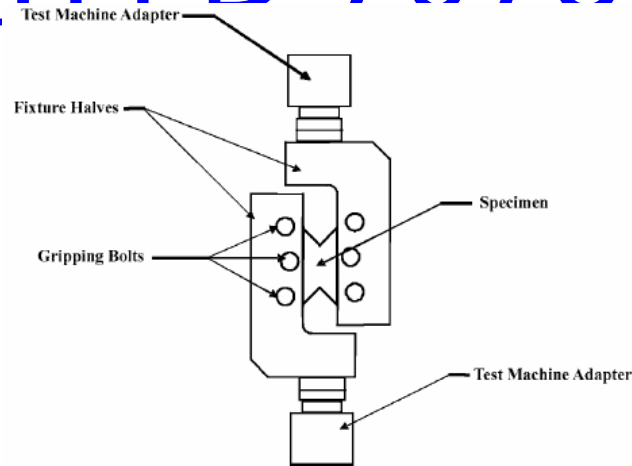
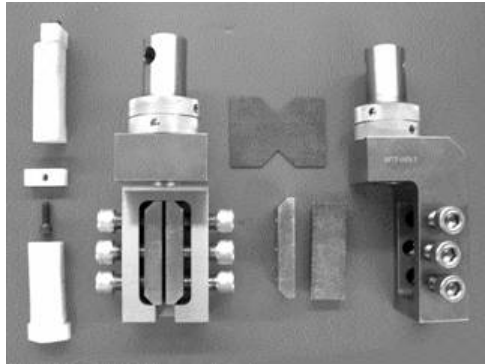


Common Unacceptable Failure Modes
(Typically Initiated At Loading Points)



Smykový vzorek s V vrubem

ASTM D 7078

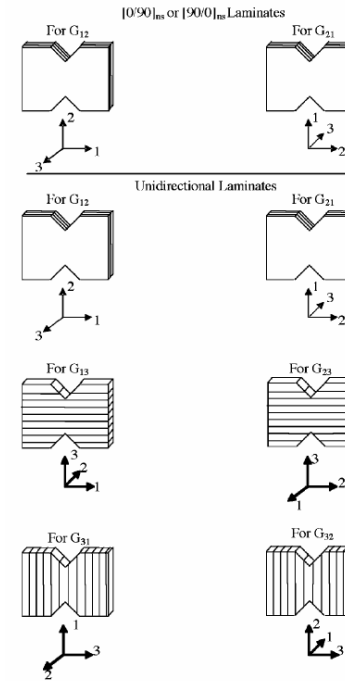
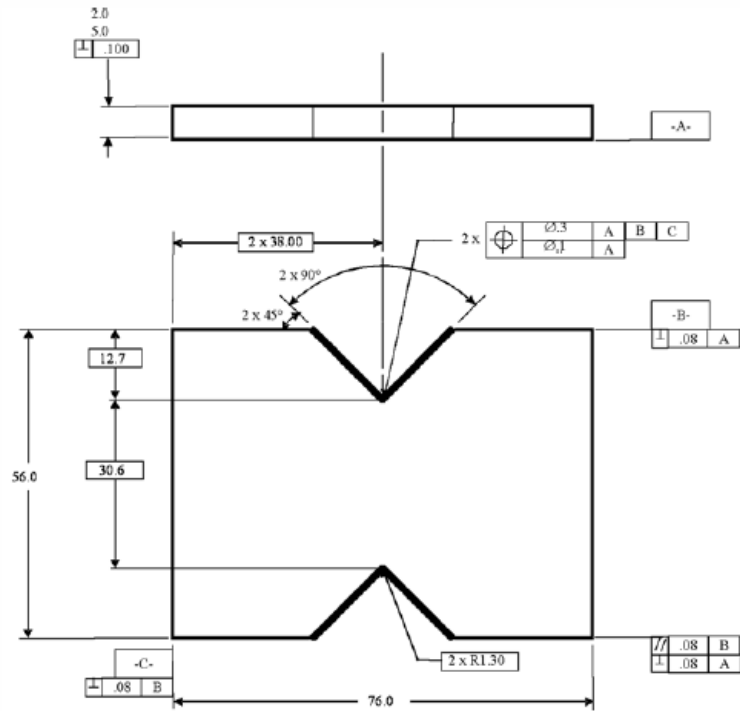


$$F^u = \frac{P^u}{w \cdot h}, \tau_i = \frac{P_i}{w \cdot h}$$

$$\gamma = \left| \varepsilon_{45^\circ} \right| + \left| \varepsilon_{-45^\circ} \right| \quad G = \frac{\Delta \tau}{\Delta \gamma}$$

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ASTM D 7078

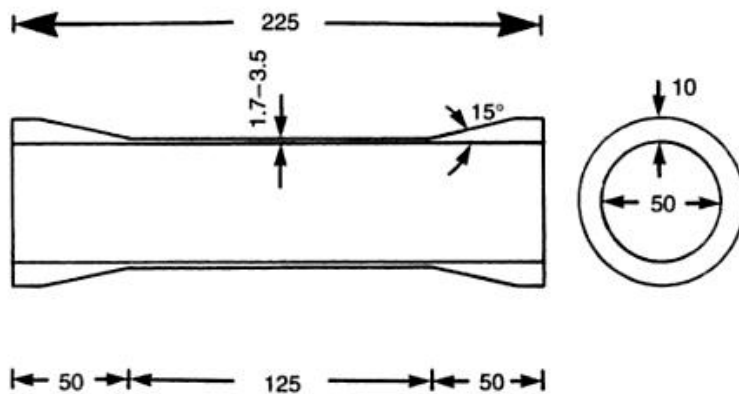


Krut tenkostěnné trubky

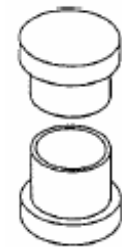
ASTM D 5448

$$\tau_{xy} = \frac{2TR_o}{\pi(R_o^4 - R_i^4)}$$

$$G_{12} = \frac{\Delta\tau_{xy}}{\Delta\gamma_{xy}} = \frac{\Delta\tau_{xy}}{\Delta(\varepsilon_{45} - \varepsilon_{-45})}$$

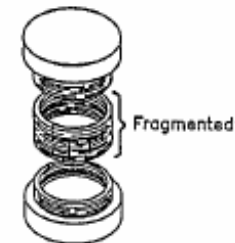


2)



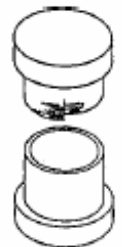
CLASSICAL

(CL)



CATASTROPHIC

(CA)



LOCAL
INSTABILITY

(LI)



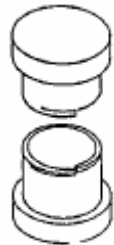
PARTIAL

(PA)



BAND
SPIRAL

(BS)

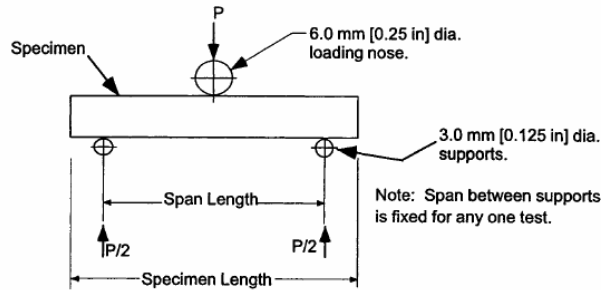


BAND
DETACHMENT

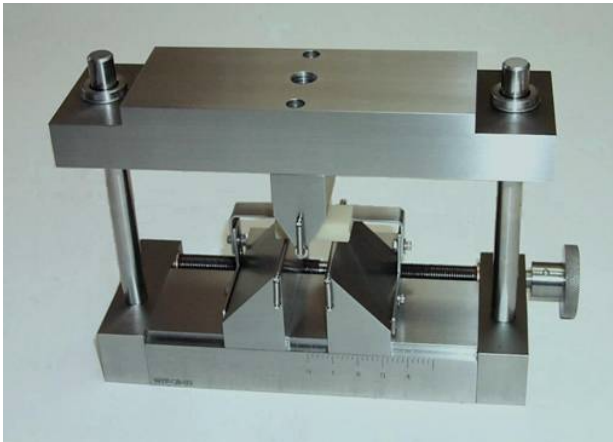
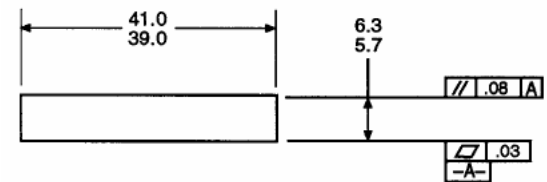
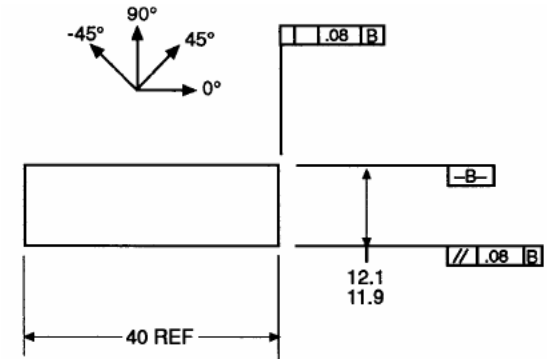
(BD)

Smyk krátkého nosníku

ASTM D 2344



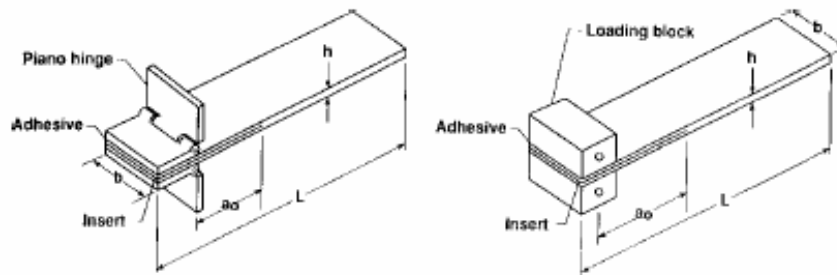
$$F^{sbs} = 0.75 \frac{P_m}{bh}$$



<http://www.wyomingtestfixtures.com/>

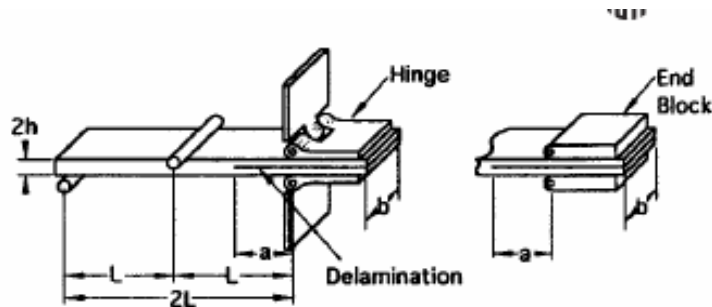
Interlaminární pevnost

Mód I [ASTM D 5528](#)



$$G_I = \frac{3P\delta}{2ba}$$

Mód I+mód II [ASTM D 6671](#)

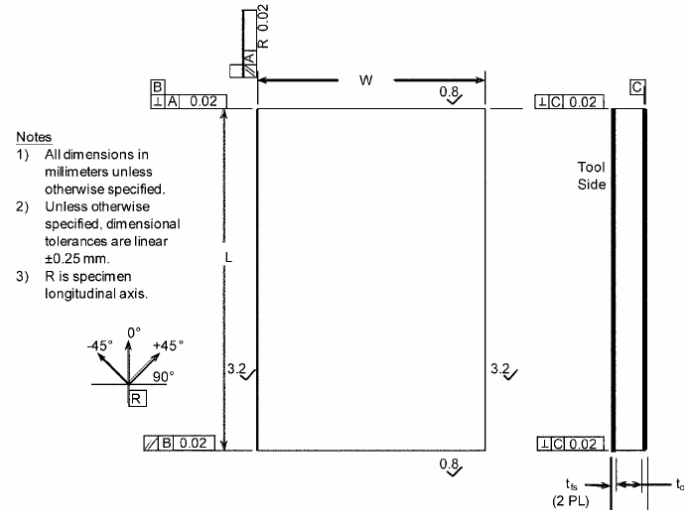
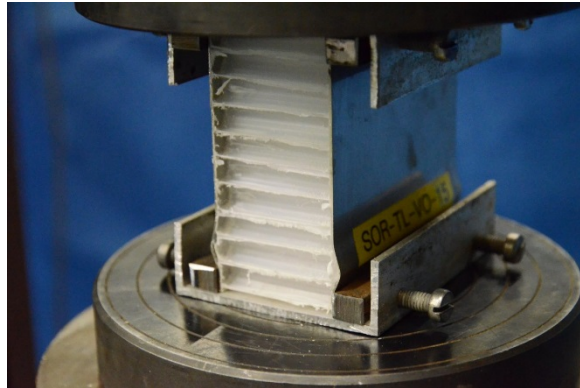


Sendviče

- Tah [ASTM C 297](#)
- Tlak [ASTM C 364](#), [C 365](#), [D7336](#)
- Smyk [ASTM C 273](#), [C393](#)
- Ohyb [ASTM D 7249](#), [D 5467](#)
- Impact ASTM 7766

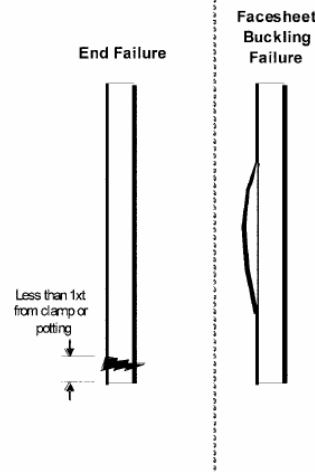
Příčný tlak ASTM C 364

$$\sigma = \frac{P_{\max}}{w(2t_{fs})}$$

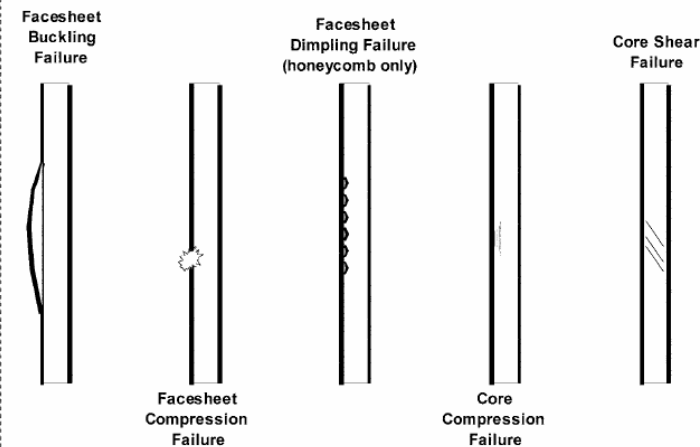


1. znak	2. znak	3. znak
Mód poruchy	Plocha poruchy	Místo poruchy
Facesheet compression	F At end	A Top T
Facesheet delam. Buckling	B Gage	G Bottom B
Honeycomb Facesheet	D Various	V Middle M
Dimpling		
Core Compression	C Unknown	U Various V
Core Shear	S	Unknown U
Multi-mode	M	
Overall Panel buckling	P	
eXplosive	X	
Other	O	

Unacceptable

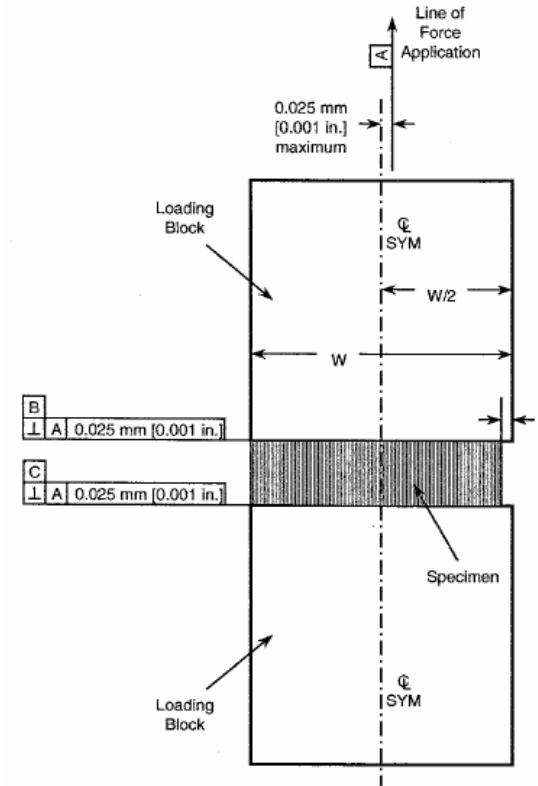
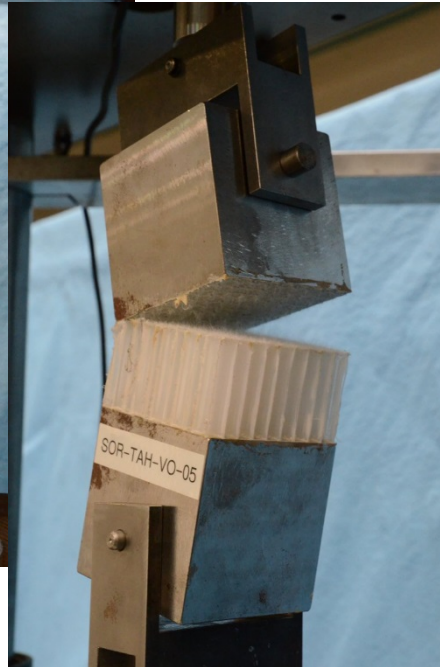
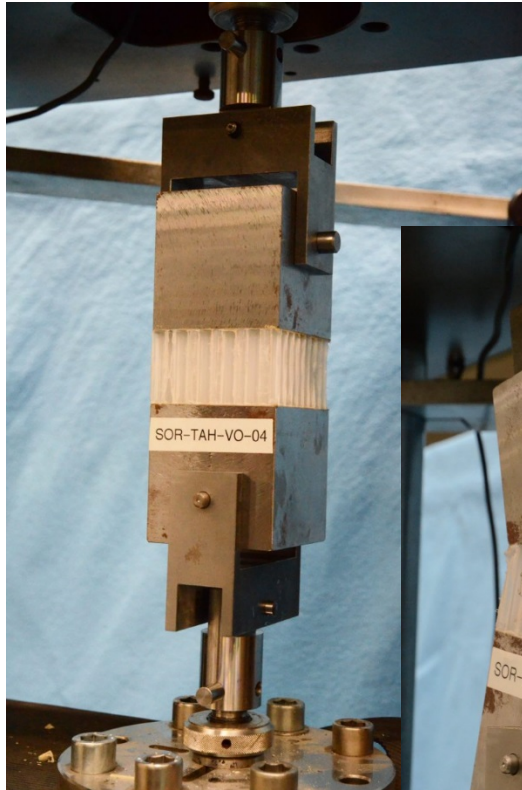


Acceptable Failure Modes



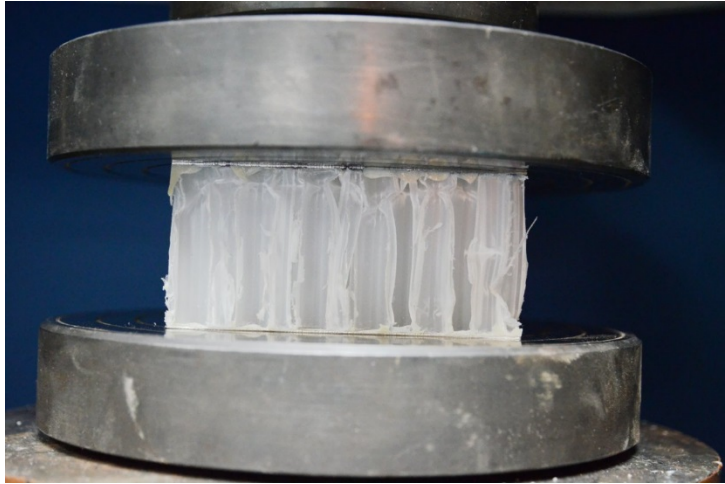
Tah ASTM C 297

$$F_z^{ftu} = \frac{P_{\max}}{A}$$



velikost buňky		min. ploch vzorku
min [mm]	max [mm]	[mm ²]
...	3	625
3	6	2500
6	9	5625

Tlak ASTM C 365

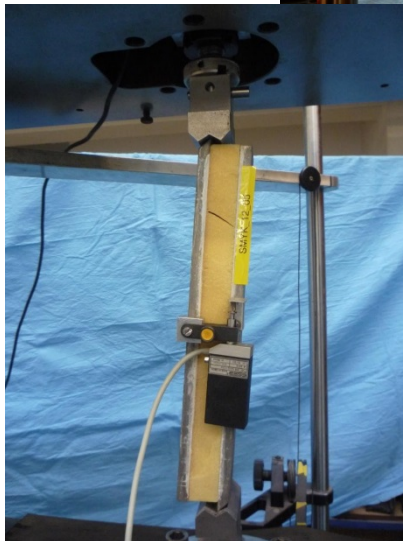
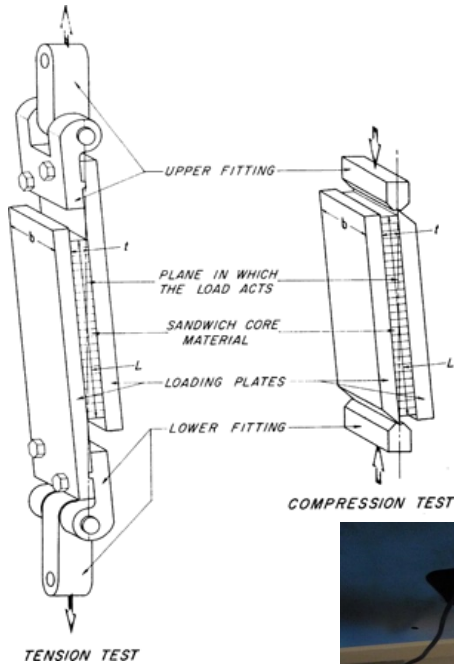


$$F_z^{fcu} = \frac{P_{\max}}{A}$$
$$E_z^{fc} = \frac{(P_{0,003} - P_{0,001}) \cdot t}{(\delta_{0,003} - \delta_{0,001}) \cdot A}$$

velikost buňky		min. ploch vzorku
min [mm]	max [mm]	[mm ²]
...	3	625
3	6	2500
6	9	5625



Smyk jádra ASTM C273

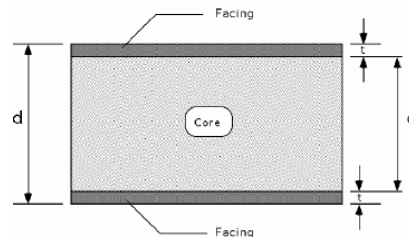
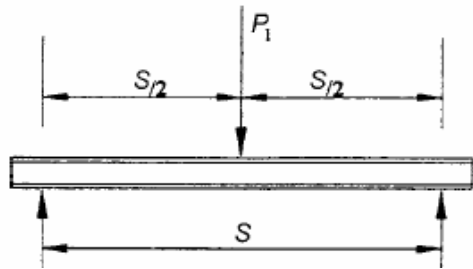


$$\tau = \frac{P}{Lb} \quad \gamma = \frac{u}{t}$$

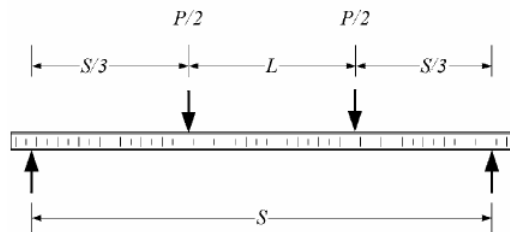
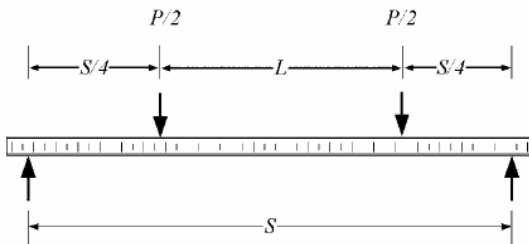
$$G = \frac{(\Delta P / \Delta u)t}{Lb}$$

1. znak	2. znak	3. znak	
Mód poruchy	Plocha poruchy	Místo poruchy	
Core Shear	S At end	A Top	T
Interface failure	Gage	G Bottom	B
eXplosive	X One Corner	C Middle	M
Other	O Various	V Entire Length	E
	Unknown	U Various	V
		Unknown	U

Smykové vlastnosti jádra z ohybu sendviče ASTM C 393



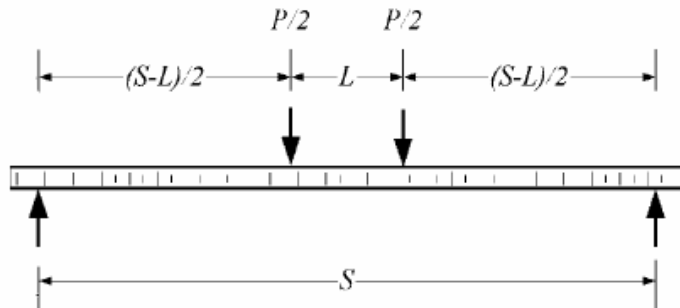
$$F_s^{ult} = \frac{P_{max}}{(d + c)b}$$



1. znak	2. znak	3. znak
Mód poruchy	Plocha poruchy	Místo poruchy
core Crushing	C At load bar	A Core
skin to core Delamination	D Gage	G Core-facing bond
Facing failure	F Multiple areas	M Bottom facing
Multi-mode transverse Shear	M One Corner S Various	C Top facing V both Facing
eXplosive	X Unknown	U Various
Other	O	Unknown

Vlastnosti potahů z ohybu dlouhých nosníků

ASTM D 7249



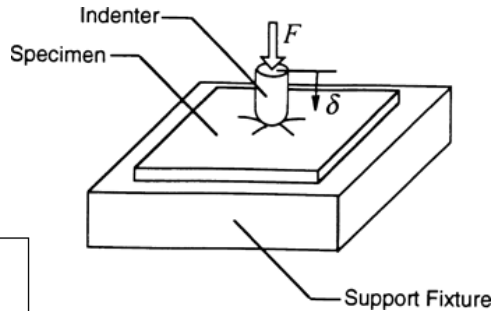
konfigurace		Vzdálenost podpor	Vzdálenost sil
Standardní	4PB	560 mm	100 mm
Nestanadrdní	3PB	\$S\$	0
	4PB čtvrtinová	\$S\$	\$S/2\$
	4PB třetinová	\$S\$	\$S/3\$

$$F^u = \frac{P_{\max} (S - L)}{2(d + c)bt}$$

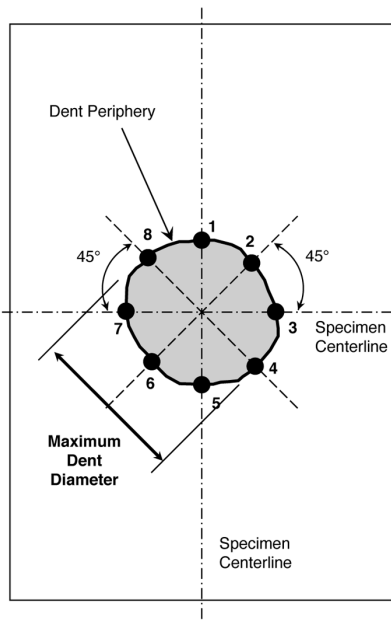
1. znak	2. znak	3. znak	
Mód poruchy	Plocha poruchy	Místo poruchy	
core Crushing	C At load bar	A Core	C
skin to core Delamination	D Gage	G Core-facing bond	A
Filament fracture	F Multiple areas	M Bottom facing	B
through-thickness	H Outside gage	O Top facing	T
Layer instability	L Various	V both Facing	F
Multi-mode longitudinal splitting	M Unknown	U Various	V
teNsile	P	Unknown	U
local Wrinkling	N		
transverse Shear	W		
explosive	S		
Other	X		
	O		

Odolnost na impakt ASTM 7766

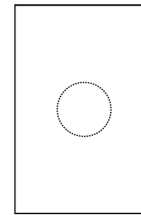
- Modifikace ASTM 6264, 7136 (vlák. komp.)



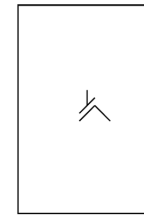
$$E = C_F t$$



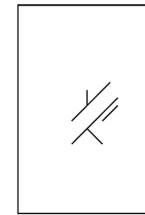
Externally Visible Damage Types



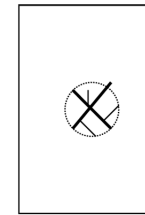
Dent/Depression



Splits/Cracks

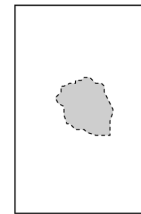


Combined Splits/Delamination (common for tape surface plies)

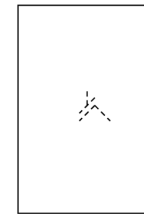


Combined Large Cracks with Fiber Breakage, Indentation/Puncture

Internal Damage Types



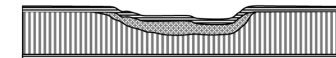
NDI Indications: Delamination/Facing-to-Core Disbond



NDI Indications: Splits/Cracks



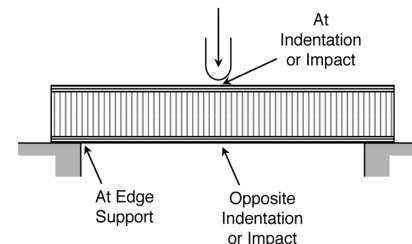
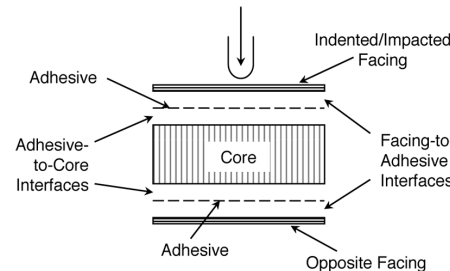
NDI Indications: Shattered Core



NDI Indications: Crushed Core






NDI Indications: Cracked Core

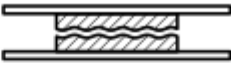
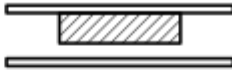




Lepené spoje

- Tah ASTM D897, ASTM D2095
- Smyk ČSN EN 1465, ASTM D 1002, EN 2243-1, D3164
- Odlup (ČSN EN ISO 11339, EN 2243-3, ASTM D3167)

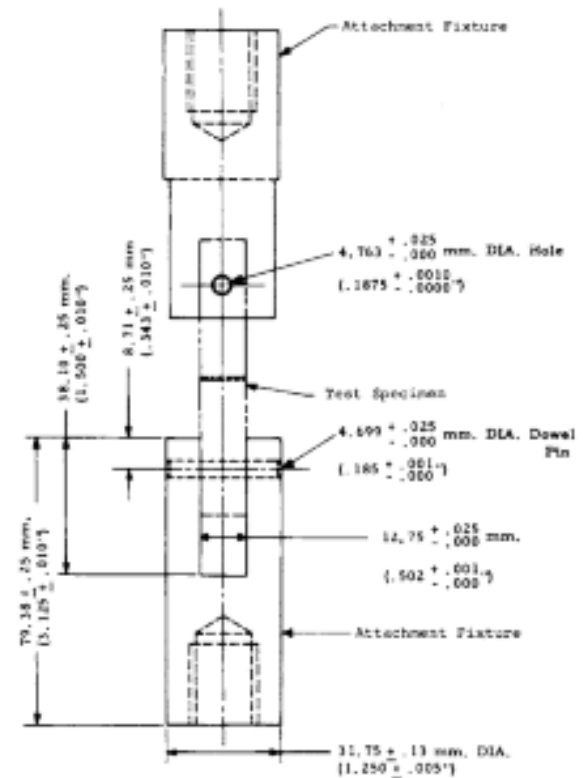
Poruchy lepených spojů

	Typ porušení		Označení
Substrát	Porušení jednoho nebo obou adherendů		SF
	Porušení jednoho adhe-rendu		CSF
	Porušení delaminační		DF

Kohezní porušení		CF	Adhezní porušení		AF
	Speciální kohezní porušení			SCF	
			Adhezní a kohezní porušení		ACFP

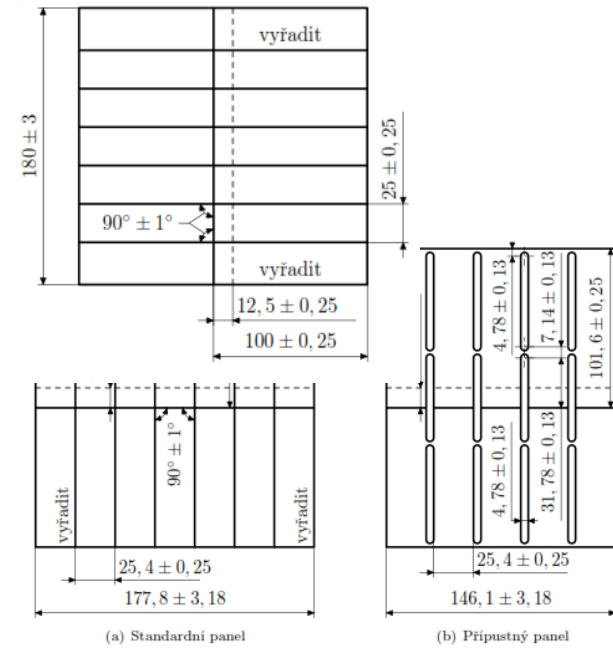
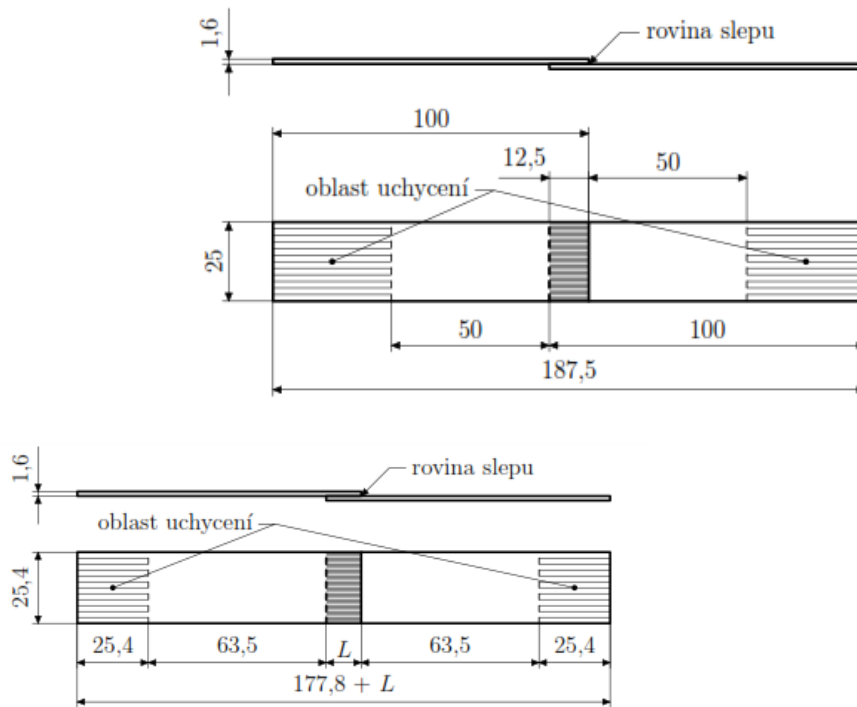
Tah

- ASTM D897, ASTM D2095



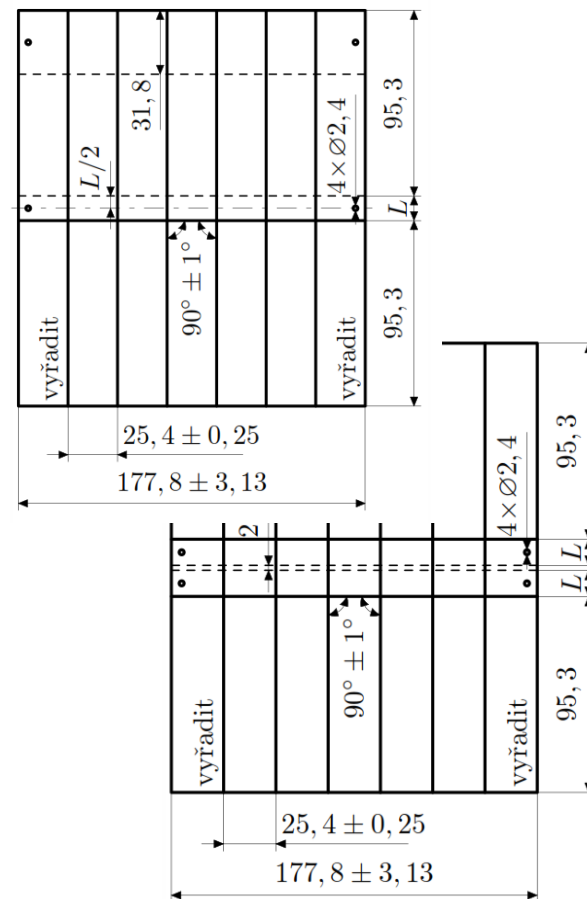
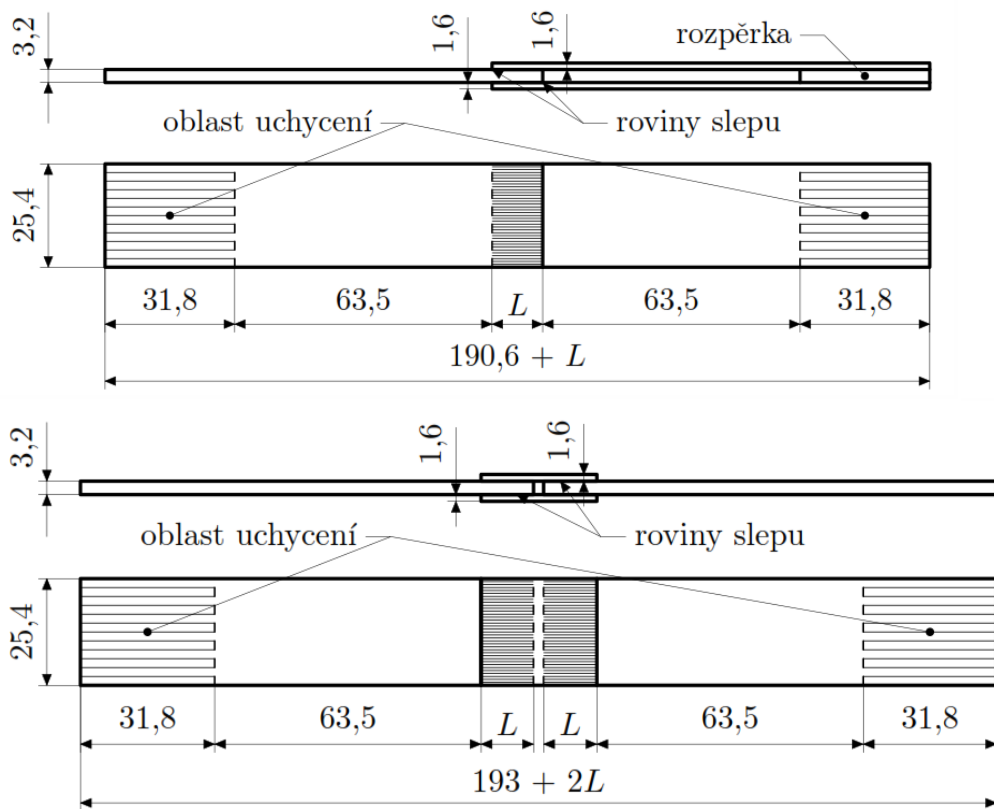
Smyk

- ČSN EN 1465, ASTM D 1002, EN 2243-1, D3164



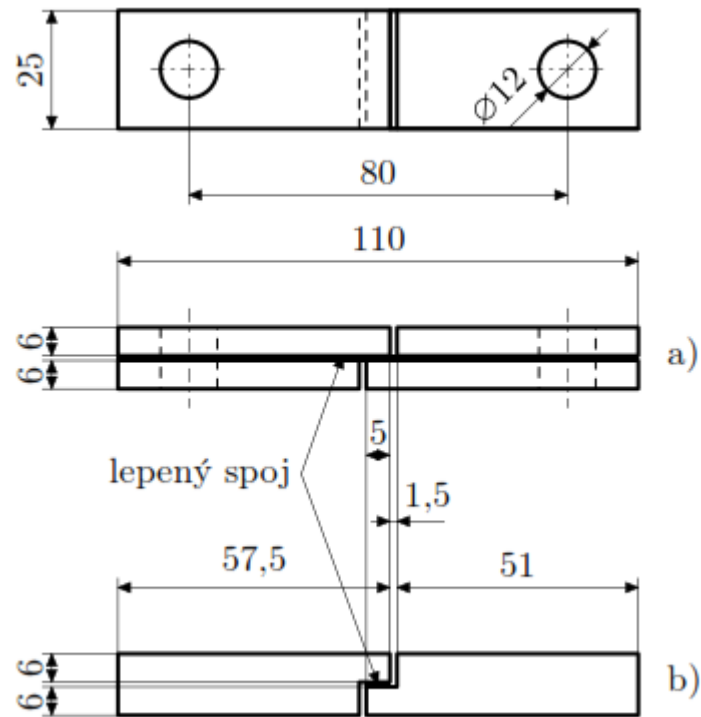
Smyk

- ASTM D 3528



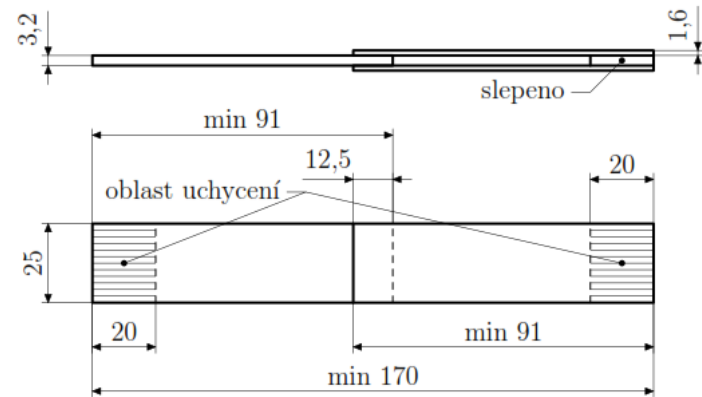
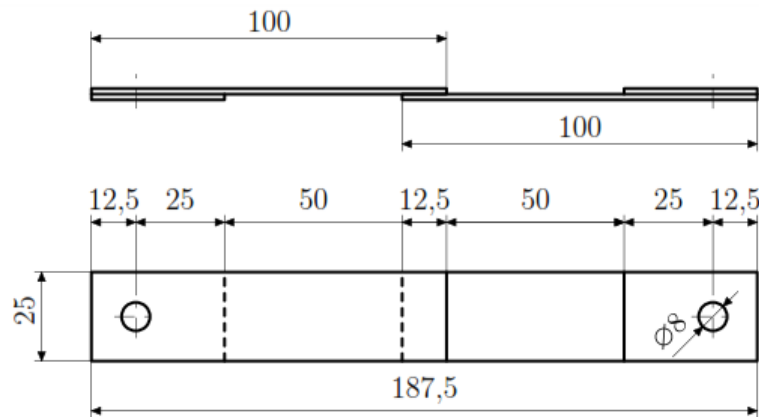
Smyk

- ČSN EN 14869-2

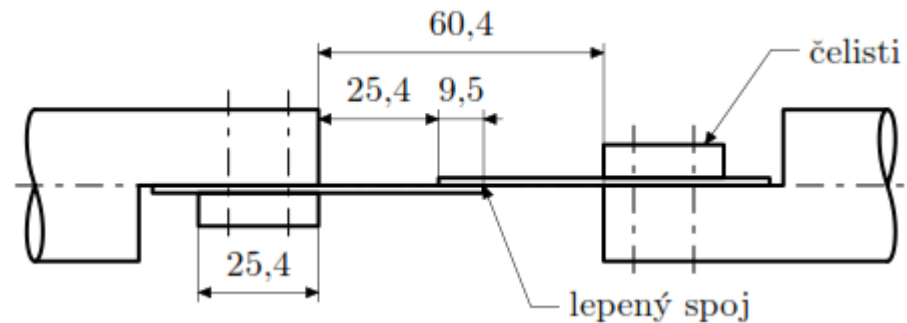


Smyk cyklické zatížení

- ČSN EN ISO 9664

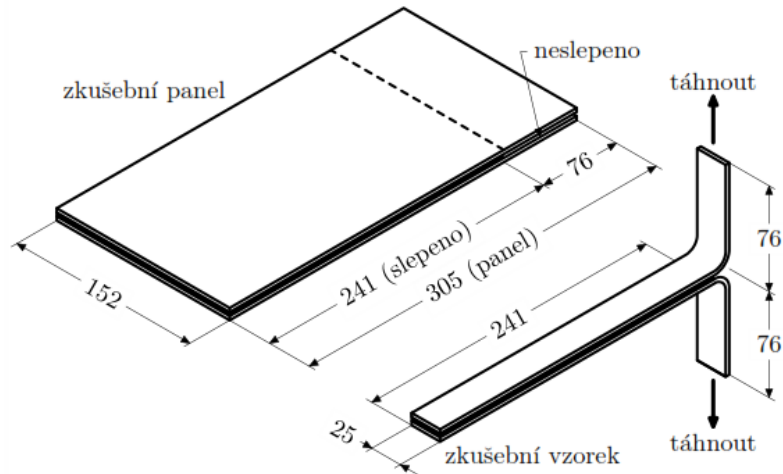
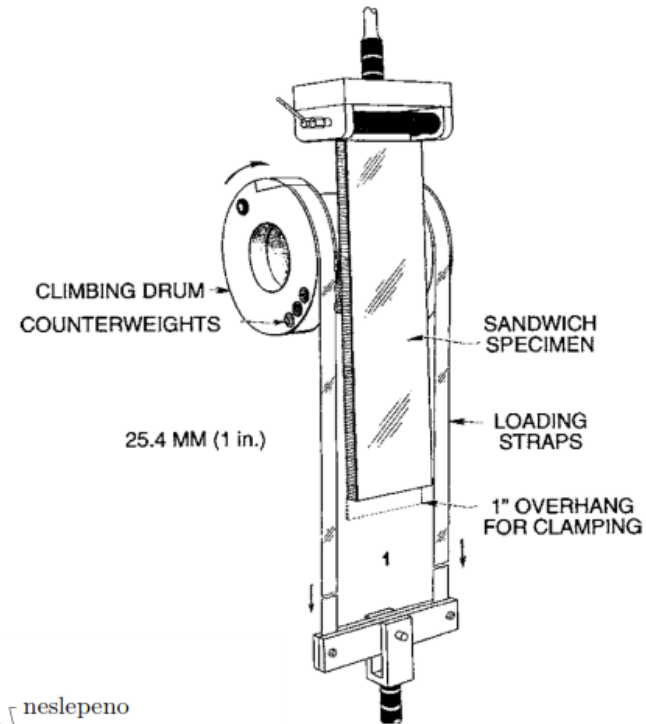


- ASTM D3166



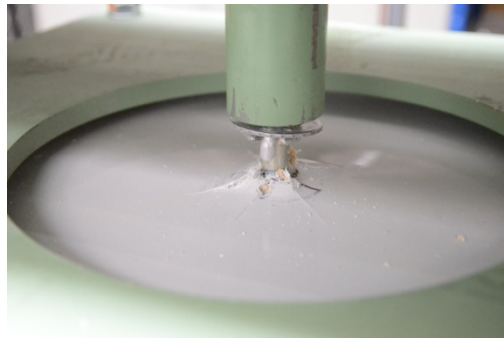
Odlup

- ČSN EN2243 ASTM D1786
- ČSN ASTM D1876



Inserty

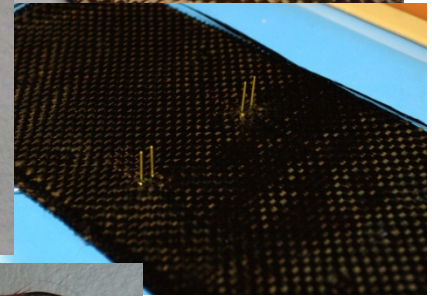
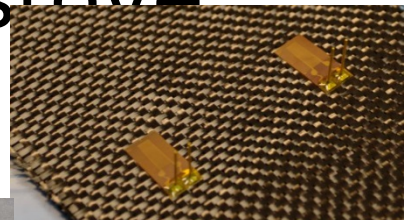
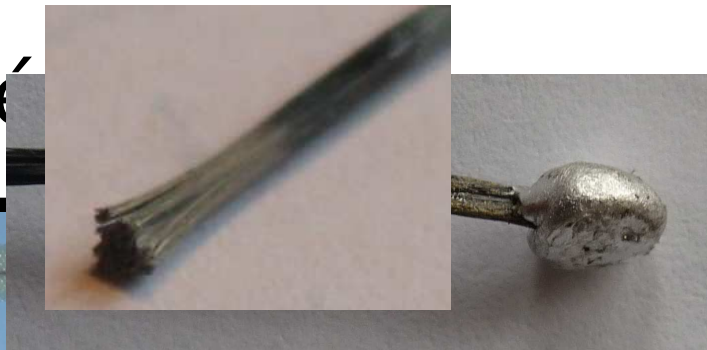
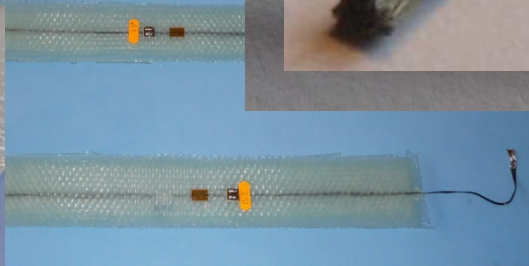
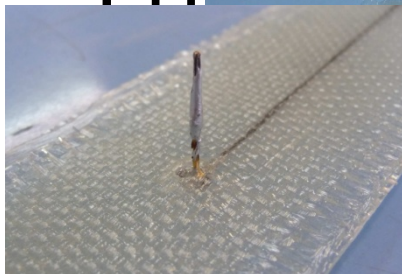
- Tah (vytrhávání)
- Smyk
- Krut



Zdroje: ASTM Standards

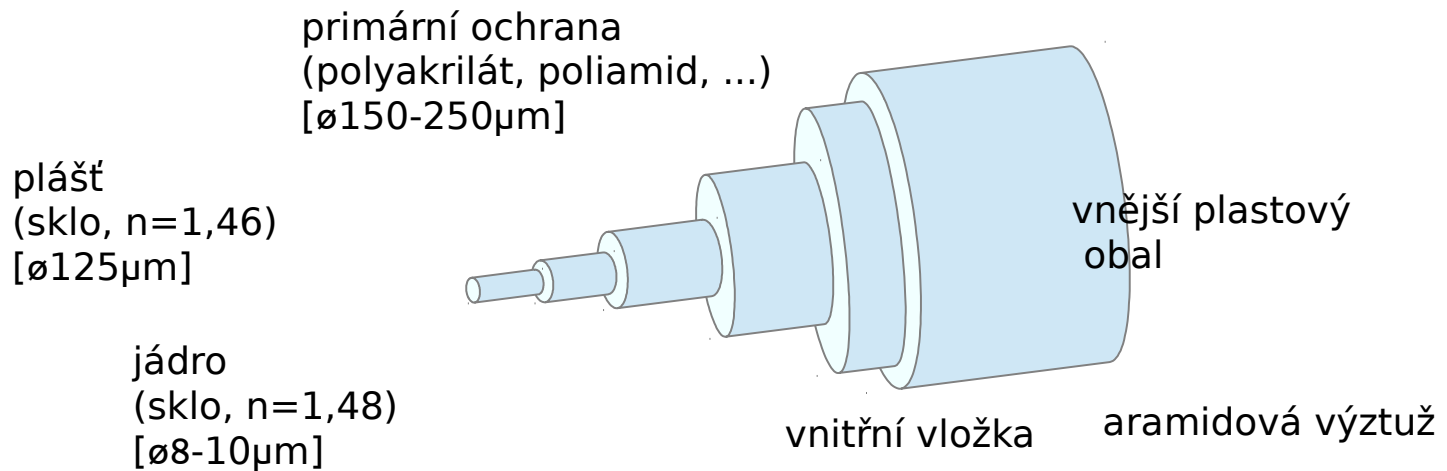
Odporová tenzometrie na kompozitních konstrukcích

- Velikost (6mm)
- Odpor 350Ω , napájecí napětí → tepelný výkon
- Teplotní kompenzace (půlmostové zapojení)
- Dvousložkové
- Příprava povrchu



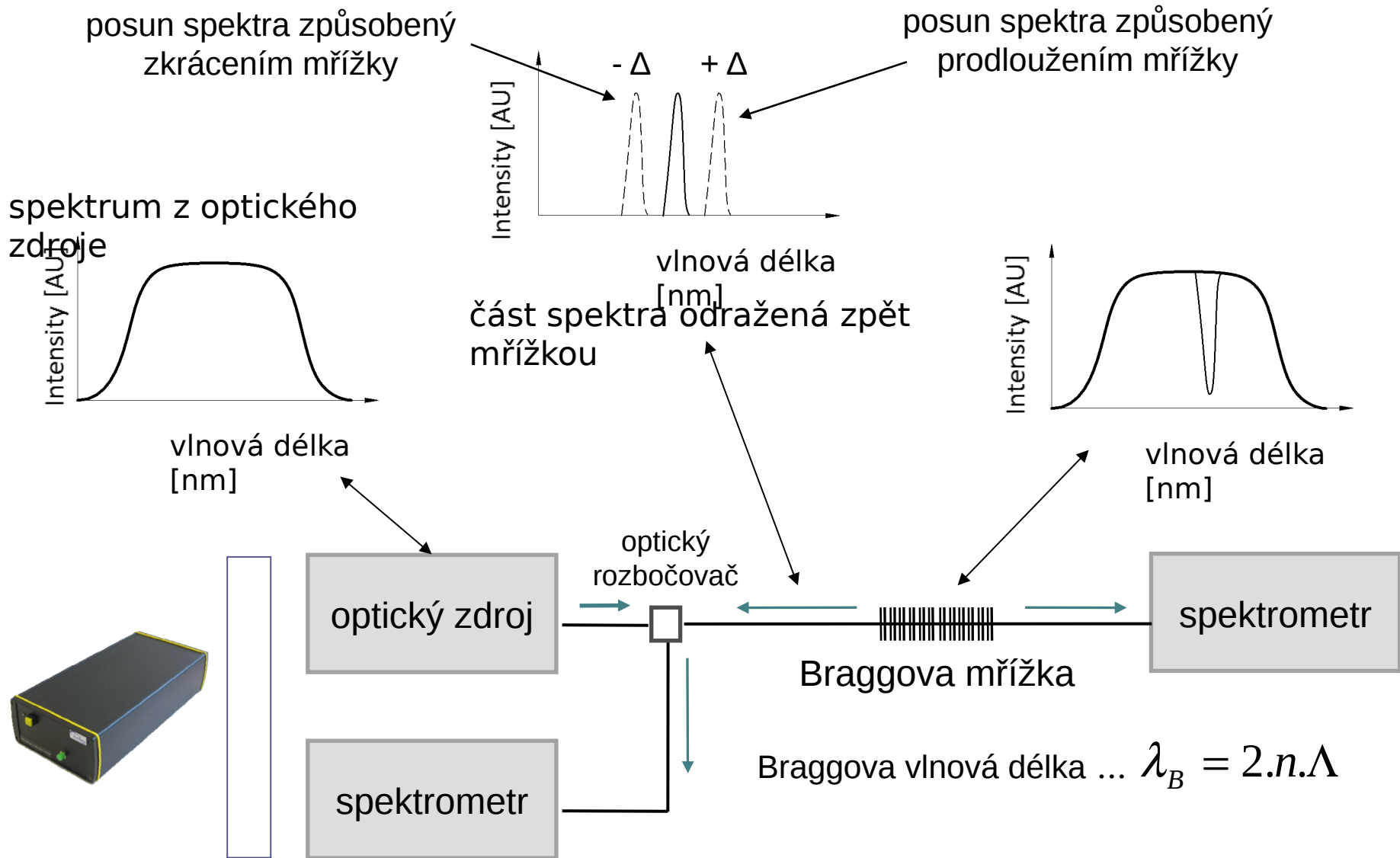
- Optická vlákna
- Plošné sledování deformací
 - Moiré
 - DIC, ESPI, Sherografie
- NDT
 - AE

Optické vlákno



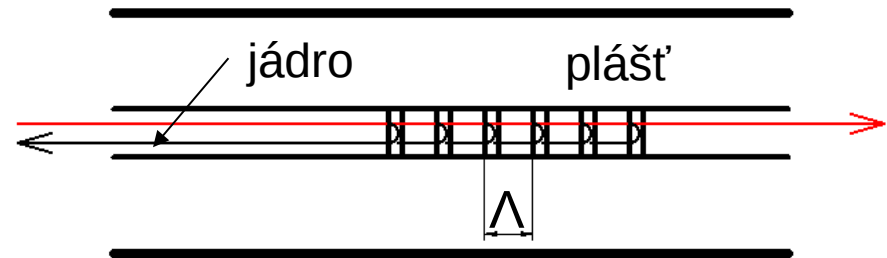
Optické vlákno

Ochrana optického vlákna



Braggova vln. délka ... $\lambda_B = 2.n.\Lambda$

n ... efektivní index lomu jádra opt. vlákna
 Λ ... perioda mřížky [nm]



Relativní změna změna Braggovy vlnové délky způsobená deformací a změnou teploty

$$\frac{\Delta\lambda_B}{\lambda_B} = k_\varepsilon \cdot \varepsilon + k_T \cdot \Delta T$$

$$\Delta\lambda_{B_{STRAIN}} = \lambda_B \cdot (1 - p) \cdot \varepsilon$$

$$\Delta\lambda_{B_{TEMP.}} = \lambda_B \cdot (\alpha + \xi) \cdot \Delta T$$

k_ε ... defomační koeficient

k_T ... teplotní koeficient teploty

p ... defomačně optický koeficient

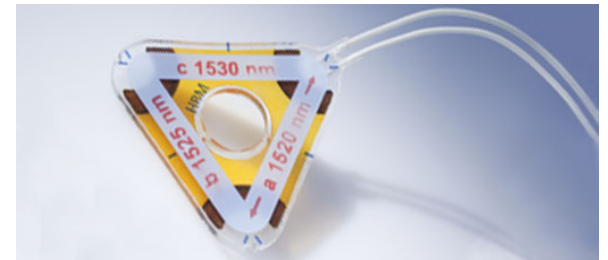
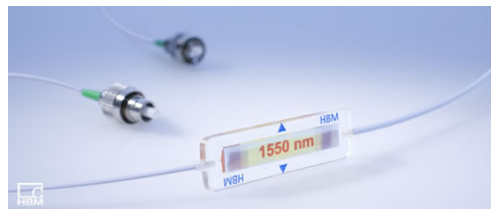
α ... koeficient teplotní roztažnosti opt. vlákna

ξ ... teplotně optický koeficient

Aparatury

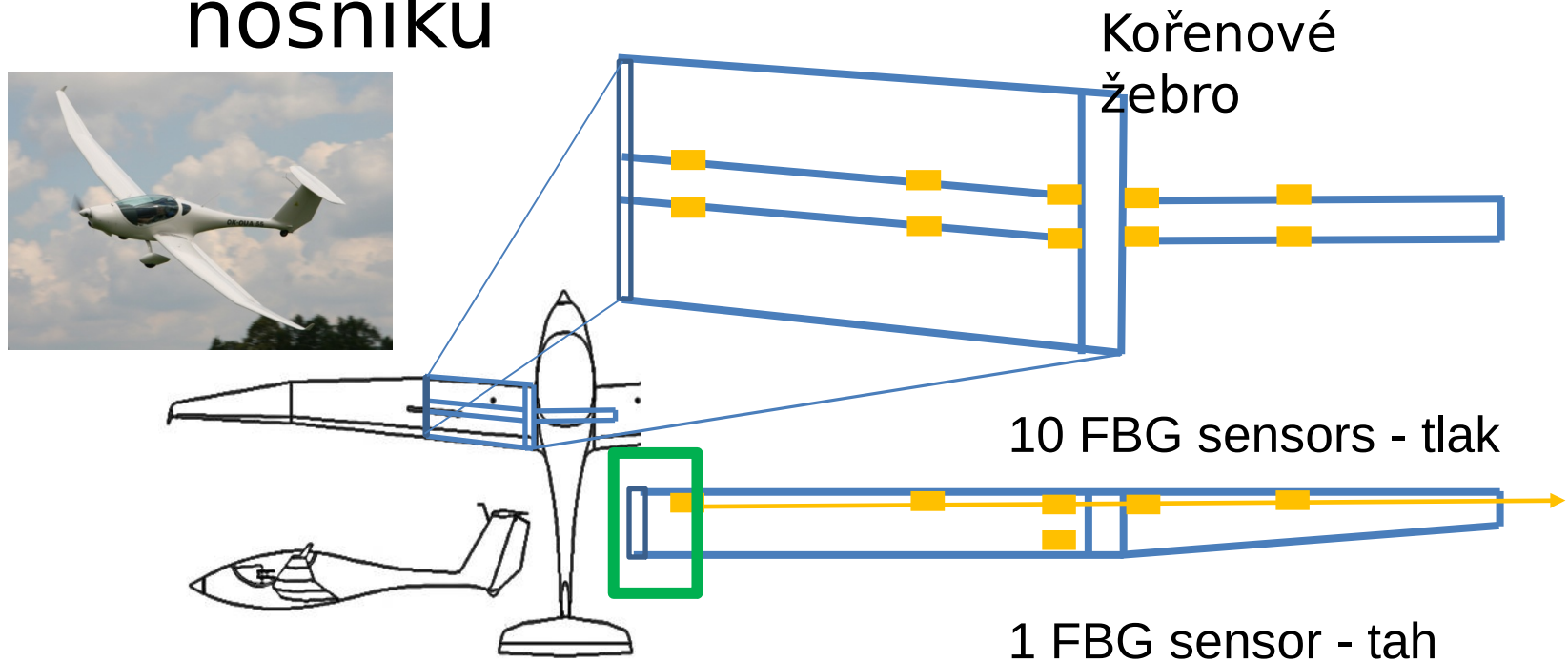


sm125 Fi

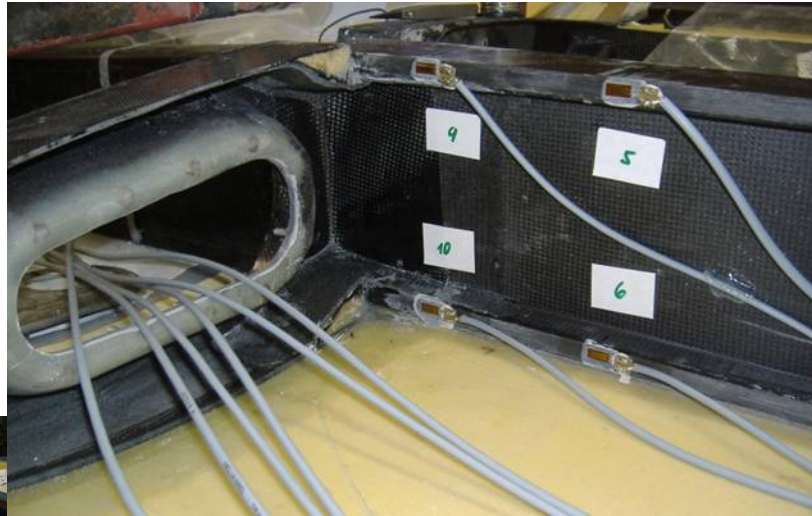


Aplikace - sledování křídla

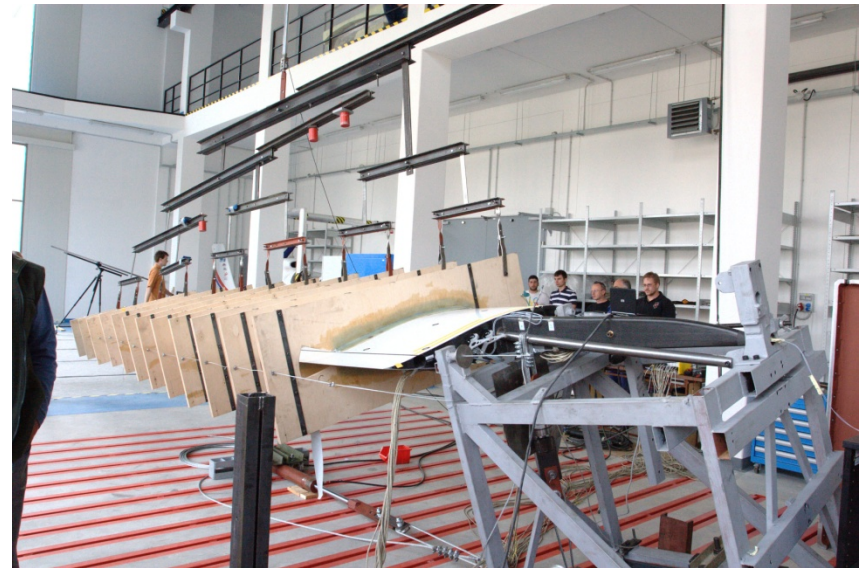
- Křídlo letadla kategorie UL Phoenix Air U15
- 2 vlákna 11 snímačů v hlavním nosníku



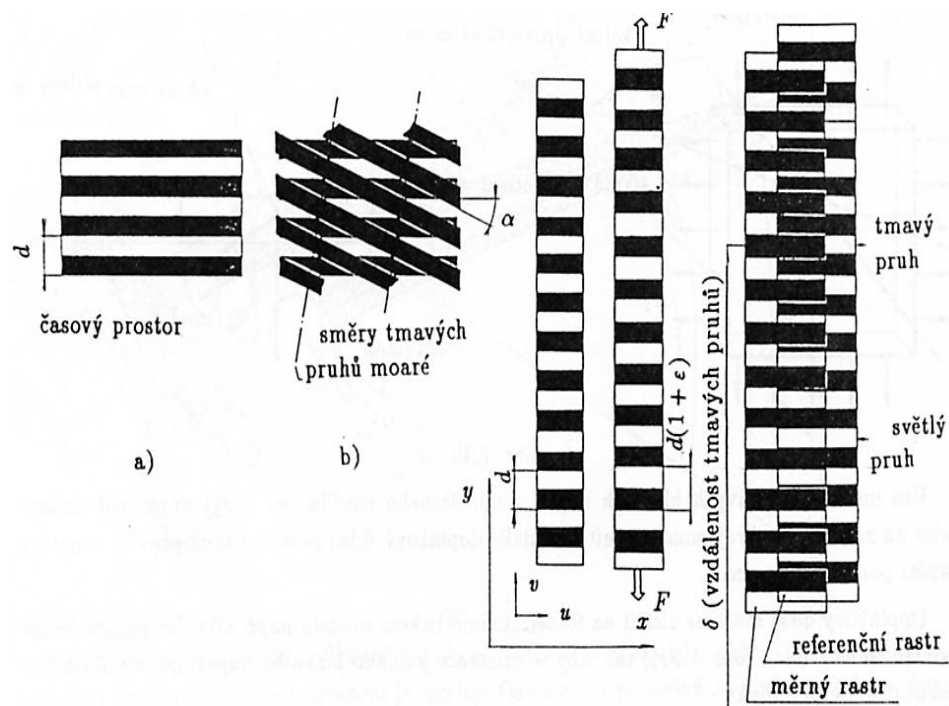
- Instalace – Phoenix Air Ústí nad Orlicí



- Statická destrukční zkouška (VUT Brno)



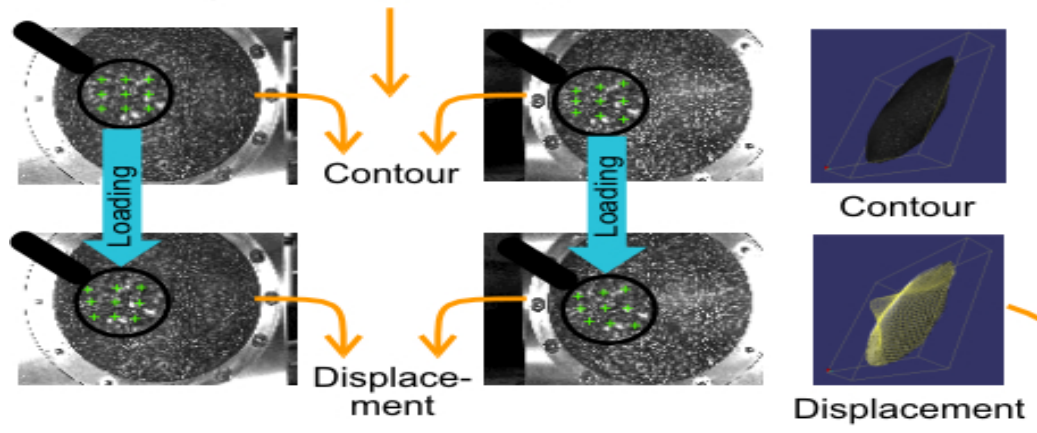
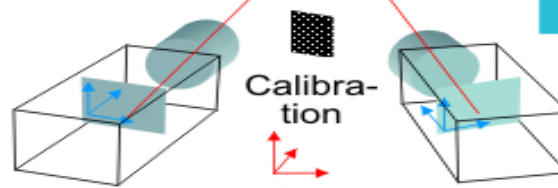
Moiré



Digitální korelace obrazu

Loading conditions

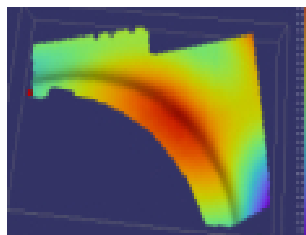
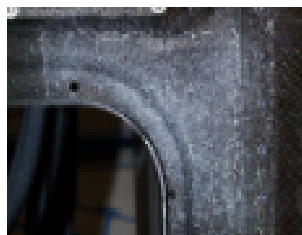
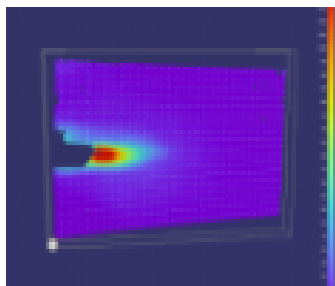
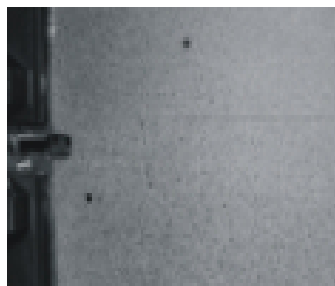
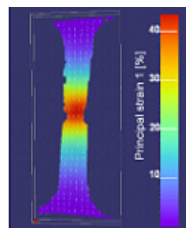
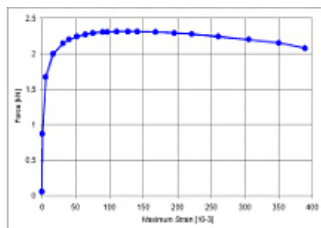
- Mechanical
- Thermal
- Vibration
- Pressure
- And others



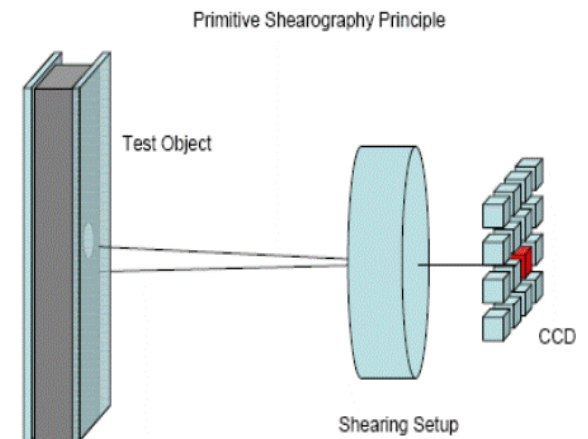
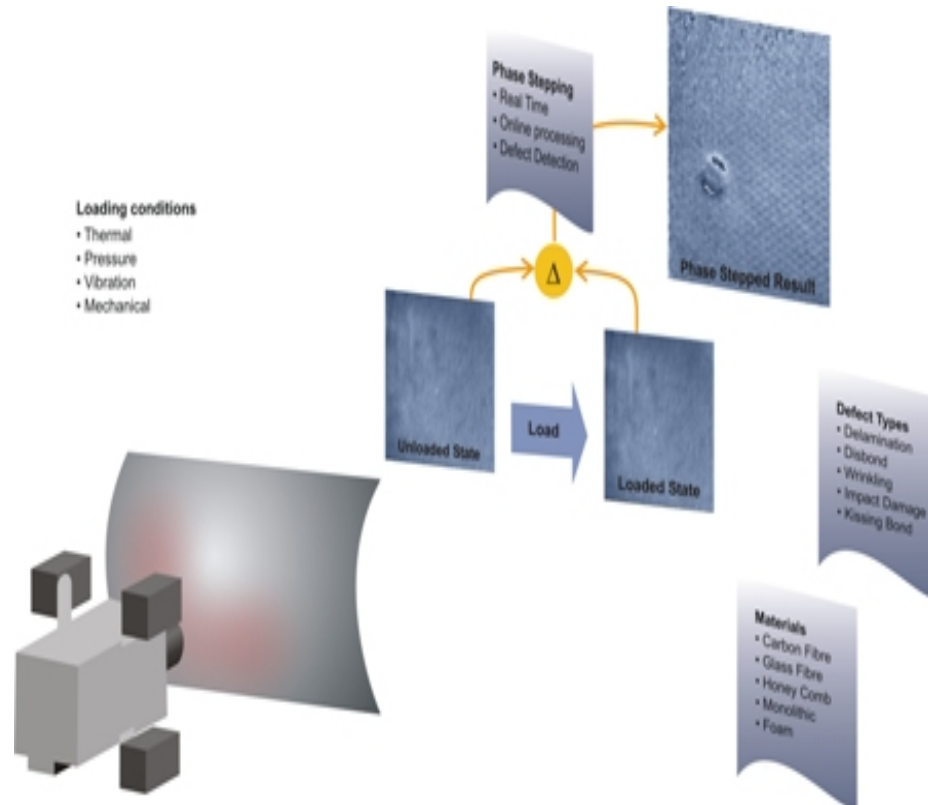
Resulting data

- | | |
|---|--|
| Static <ul style="list-style-type: none"> • 3-D displacement • Strain • Defects | Dynamic <ul style="list-style-type: none"> • 3-D displacement • Amplitude of vibration • Defects |
|---|--|

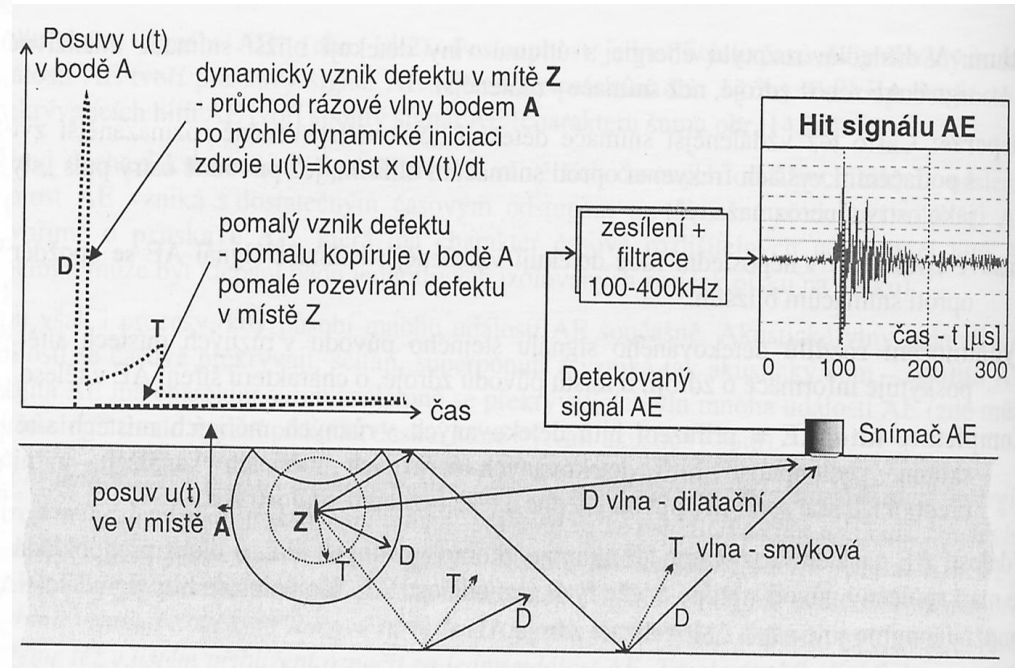
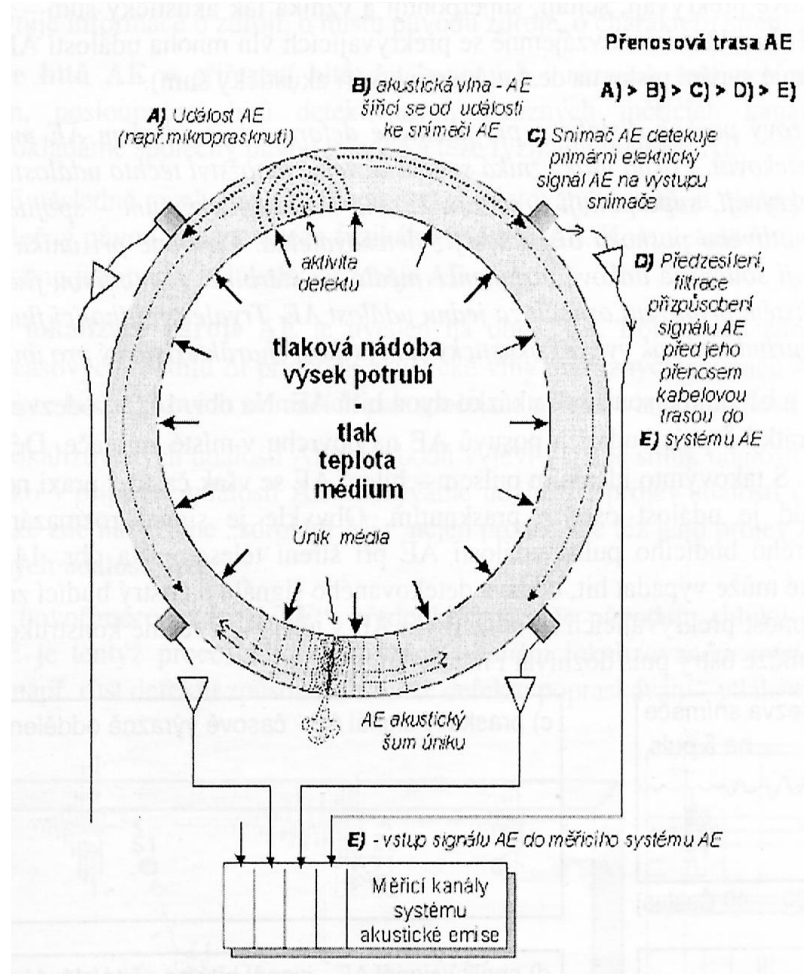
Data evaluation



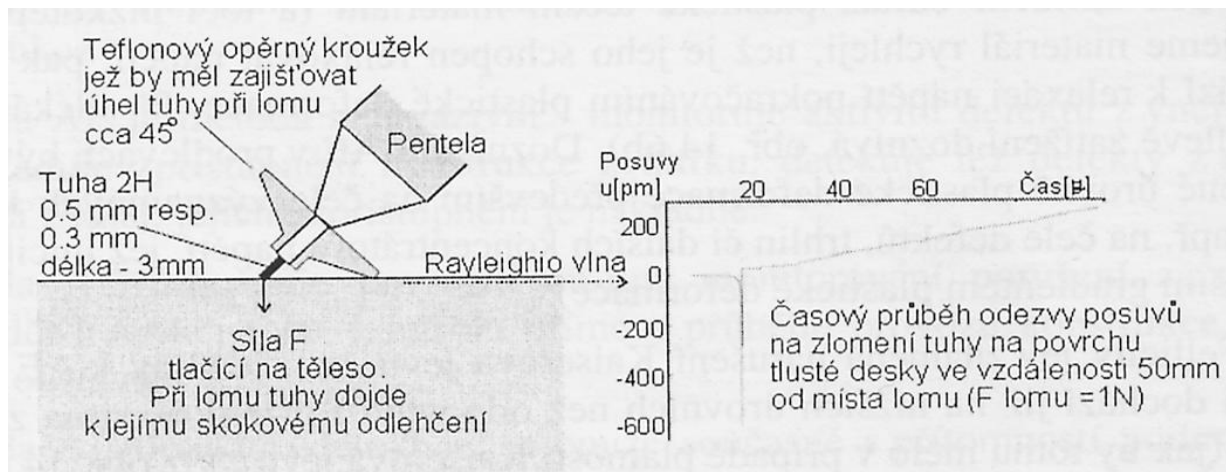
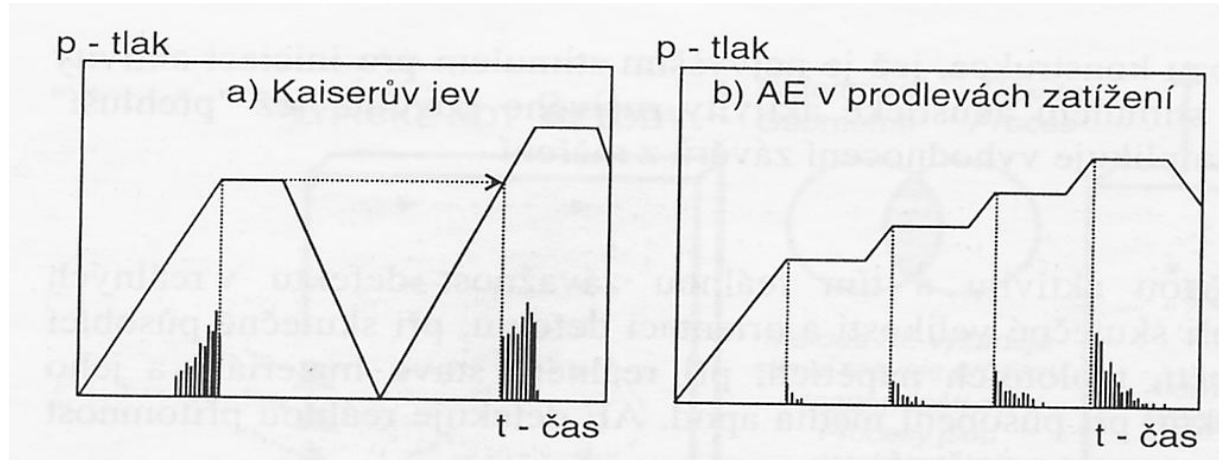
Sherography



Akustická emise



Akustická emise



Zdroje

- 1) Mallick, P. K. *Composites Engineering Handbook*, CRC Press, 1997, ISBN 0824793048
 - 2) Hodgkinson, J.M. *Mechanical testing of advanced fibre composites*, Woodhead Publishing 2000, ISBN 1855733129
 - 3) Carlsson, L.A., Adams, D.F., Pipes, R.B. *Experimental Characterization of Advanced Composite Materials, Third Edition*, CRC Press, 2002 , ISBN1587161001
 - 4) *COMPOSITE MATERIALS HANDBOOK – VOLUME 1, Polymer Matrix Composites, Guidelines for Characterization of Structural Materials MIL-HDBK-17*, US Army Research Laboratory, 2002, Fort Belvoir,
- ▣ Valenta, F. , kol.: Pružnost pevnost III, 2003, ČVUT v Praze
 - ▣ Kopec, B. a kol.:Nedestruktivní zkoušení materiálů a konstrukcí 2008, Brno,CERM
 - ▣ www.dantecdynamical.com