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Analysis of the Inclined Double Notch Shear Test for Composite Interlaminar Shear Properties

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Composite Interlaminar Shear (ILS): Why ?

Fiber composites:

- **Strong** and **stiff** along fiber direction(s)
- Exceptional **performance along fiber** direction(s)
- Nominal loadcases (almost) **never critical**
- Nominal loadcases (almost) **only in laboratory** conditions

Instead: Composite behavior and failure

- Fail along **weak directions**: Along planes with no reinforcing fibers, e.g. matrix cracking, delamination, or **between lamellae**
- **Unfavorable loads**: Transverse loads, load introduction, geometry changes, joints, contacts. All **cause ILS-stresses**
- **Engineering properties**: Strengths, moduli, srtess-strain response

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Interlaminar Shear (ILS): Difficult Testing

Fiber composites:

- Often in the shape of **thin, layered panels,** i.e **laminates**
- Fiber reinforcments mainly (only) oriented **within that plane**
- No bridging fibers between lamellae: **Weakest plane** of composite

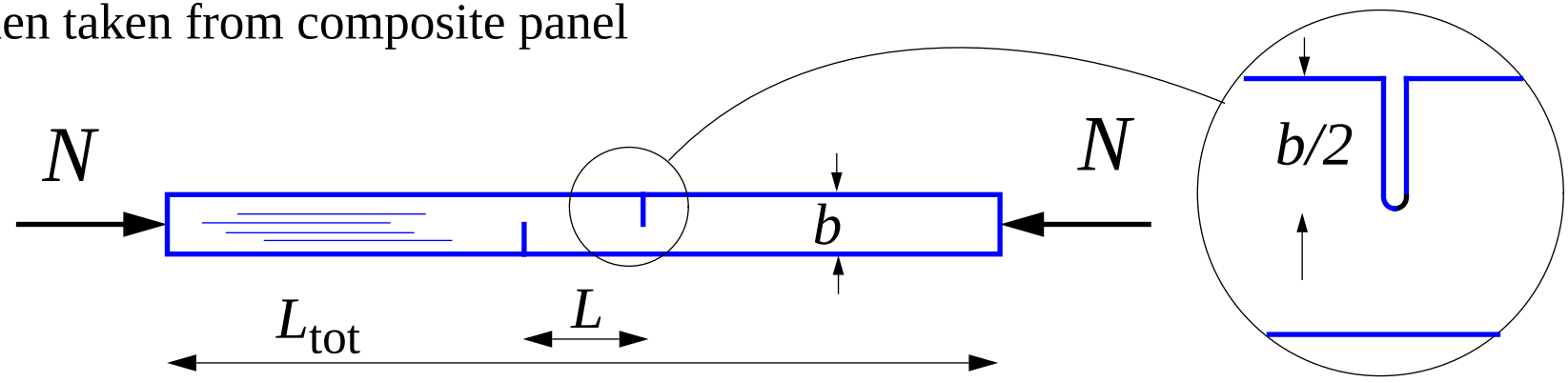
Desirable testing conditions:

- **Uniform stress state** in test region
- **Highest stress** occuring in **well defined** test region
- State of **pure stress** τ (**Interlaminar** shear **along thin** specimen)
- **Simple evaluation** (equlibrium): Net force/transferring area (***N/A***)
- **Insensitive** to elastic (**anisotropic**) properties of material

Double Notch Compression (DNC-) Test

Specimen with notches secures ILS loading and failure

Specimen taken from composite panel



Drawbacks of DNC-test:

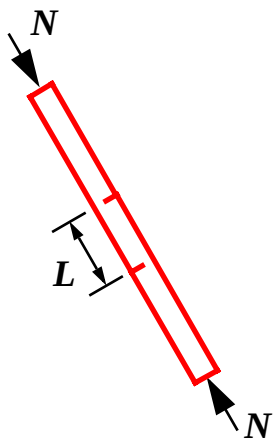
- Extremely **poor stress uniformity**
- Gives very **low** (poor) interlaminar shear strength (**ILSS-**) **values**
- Results **depend on notch distance** (specimen geometry: *L/b*)
- Failure always **initiates at notches** (measures ~toughness)

Inclined Double Notch Shear (IDNS-) Test

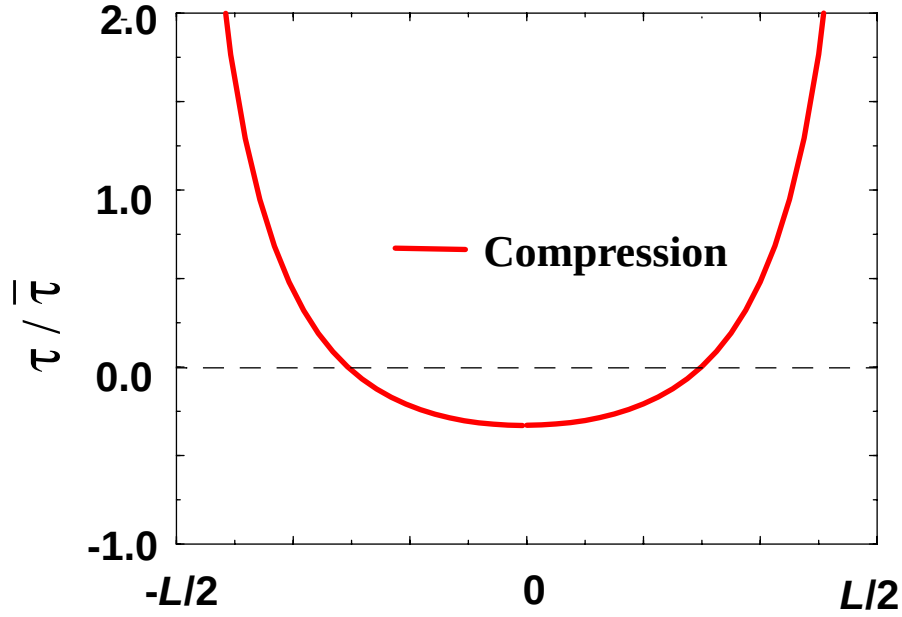
Concept - DNC specimen .....

Compression (*N*)

($\bar{\tau} = N/A$)



Shear stress between notches

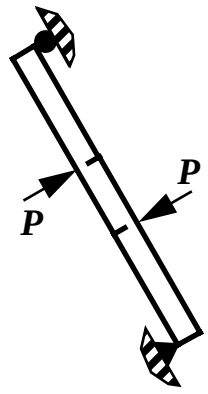


- Compression (N): Creates nominal load $\bar{\tau} = N/A$

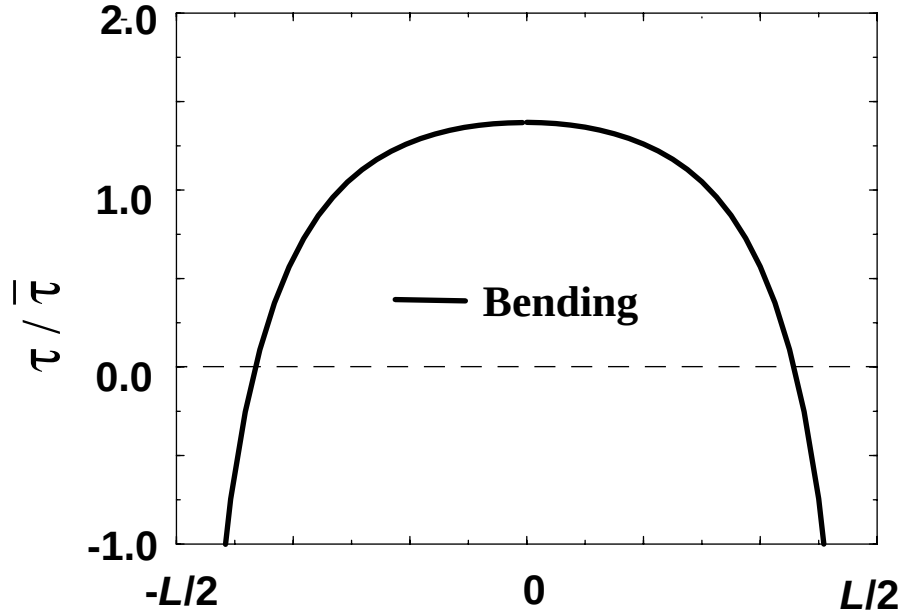
Inclined Double Notch Shear (IDNS-) Test

Concept - DNC specimen with additional loadset

Bending (*M*)
($\bar{\tau} = 0$)



Shear stress between notches



- Bending (*M*): Counteracts stress concentrations, no net-stress $\bar{\tau} = 0$

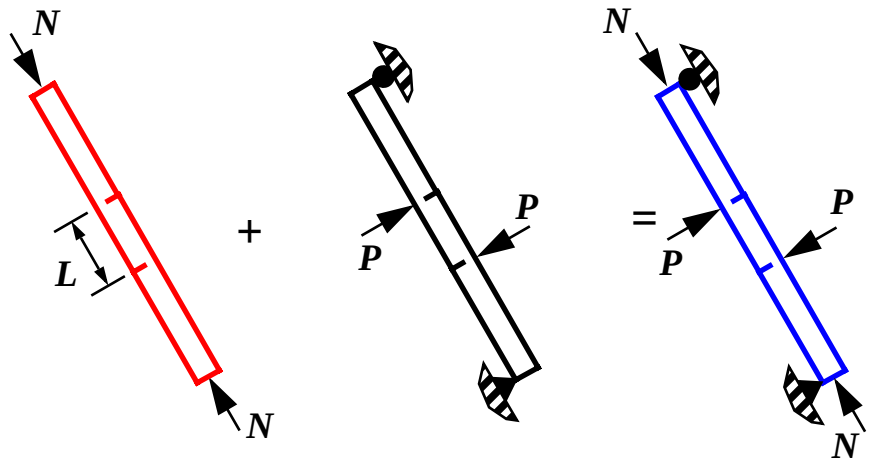
Inclined Double Notch Shear (IDNS-) Test

Concept - Optimal combination of two loadsets

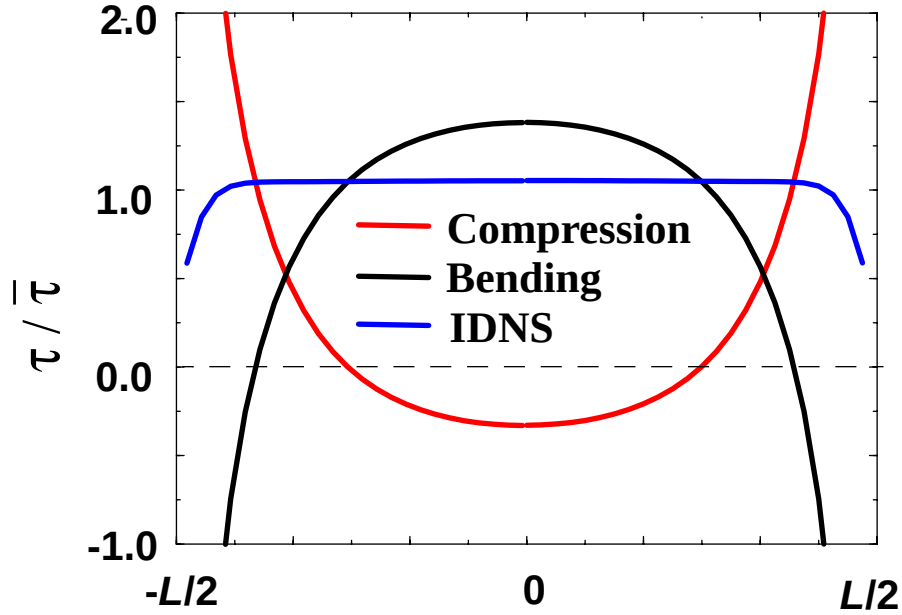
Compression (*N*) ($\bar{\tau} = N/A$)

Bending (*M*) ($\bar{\tau} = 0$)

IDNS (*N*+*M*) ($\bar{\tau} = N/A$)



Shear stress between notches



- Compression (*N*): Creates nominal load $\bar{\tau} = N/A$
- Bending (*M*): Counteracts stress concentrations, no net-stress $\bar{\tau} = 0$
- IDNS: $N + M$ in correct proportions gives optimal conditions

Inclined Double Notch Shear (IDNS-)Test

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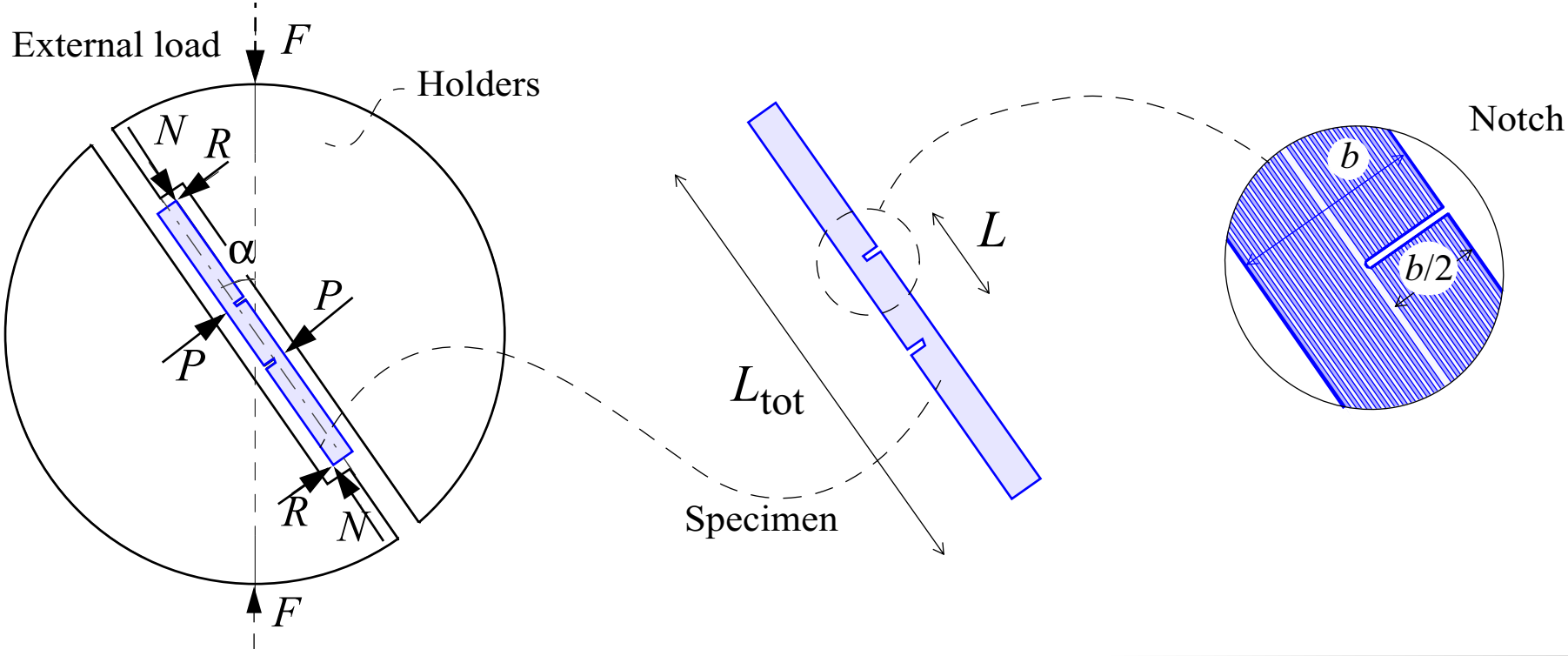
Relies on proper combination of two loadsets (*N* and *M*):

- **Proportional loading** throughout entire test is **paramount**
- This is accomplished by **supporting** specimen **with holders** in an **inclined position** α vs. the external load F
- **Proportion** among loadsets is chosen by **varying inclination** α



IDNS - Test: Analysis

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How to determine optimal combination, i.e. correct α ?

- Notches are considered as **sharp cracks**
- Stress concentrations described by **stress intensity factors K_{I}**
- **Compressive** nominal load N gives $K_{\mathrm{I}}^{N} < 0$
- Forces P and R give bending moment M and **tensile** $K_{\mathrm{I}}^{M} > 0$
- Proper combination of loadsets for **cancellation** of **total** SIF

$$K_{\mathrm{I}}^{\mathrm{tot}} = K_{\mathrm{I}}^{N} + K_{\mathrm{I}}^{M} = 0$$

- **Statically determined** loads N, P and R, and thus bending M
- These give **nominal stresses** for each case: $\sigma^{N} < 0$ and $\sigma^{M} > 0$
- Fulfilling target condition $K_{\mathrm{I}}^{\mathrm{tot}} = 0$: **Straight forward** analysis!

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IDNS - Test: Target condition $K_{\mathrm{I}}^{\mathrm{tot}} = 0$

Appropriately adjusted α fulfills target condition

- Stress intensity factors for **normal** loading (K_{I}^{N}) and for a **pure bending** moment (K_{I}^{M}) are found in **handbooks** as:
- $K_{\mathrm{I}}^{N} = 2.842\sigma^{N}\sqrt{\pi a}$ and $K_{\mathrm{I}}^{M} = 1.481\sigma^{M}\sqrt{\pi a}$ (crack depth $a = b/2$)
- Bending of **short** and **anisotropic** beam calls for adjustment of K_{I}^{M}
- Solve target condition for α, gives **closed form** equation:

$$\alpha = \operatorname{atan}\left[\frac{b(\lambda^{1/4}(2.639L + 0.639L_{\mathrm{tot}}) - 0.115b)}{\lambda^{1/4}L(L_{\mathrm{tot}} - L) - 0.115bL_{\mathrm{tot}}}\right]$$

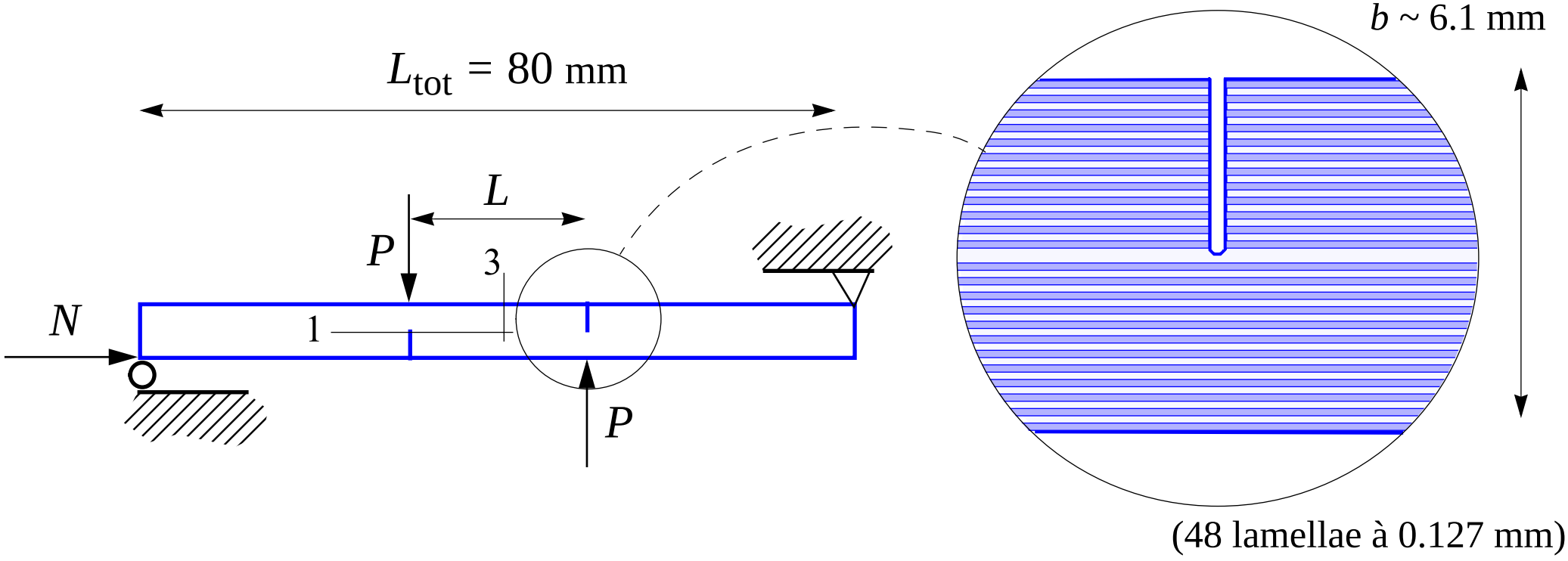
- With **specimen geometry**: L_{tot}, L and b, and its **orthotropy** λ:

$\lambda = E_3/E_1$ with through-thickness (E_3), and lengthwise (E_1) moduli

Finite Element (FE-) analysis of specimen

Determine appropriate α_{FE} and stress distributions

- **Three** different **material models** are investigated
- The specimen modelled as **isotropic**, **orthotropic**, or **laminated**



- Four different **notch distances** are studied: ***L/b*** = **1, 2, 3** and **4**

FE - analysis: Material properties

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Homogeneous orthotropic

Young's Modulus	Shear Modulus	Poisson's Ratios
E_1 = 85.0 GPa	G_{12} = 3.7 GPa	ν_{12} = 0.463, ν_{21} = 0.069
E_2 = 12.7 GPa	G_{23} = 4.8 GPa	ν_{23} = 0.069, ν_{32} = 0.463
E_3 = 85.0 GPa	G_{13} = 3.7 GPa	ν_{31} = 0.034, ν_{13} = 0.034

or made up of

Individual 0°- (and 90°) - layers

Young's Modulus	Shear Modulus	Poisson's Ratios
E_1 = 160.0 GPa	G_{12} = 4.3 GPa	ν_{12} = 0.310, ν_{21} = 0.019
E_2 = 10.0 GPa	G_{23} = 3.2 GPa	ν_{23} = 0.518, ν_{32} = 0.487
E_3 = 9.4 GPa	G_{13} = 4.8 GPa	ν_{31} = 0.018, ν_{13} = 0.310

FE - analysis: Appropriate inclination α_{FE}

and compared to closed form equation

Orthotropic models:

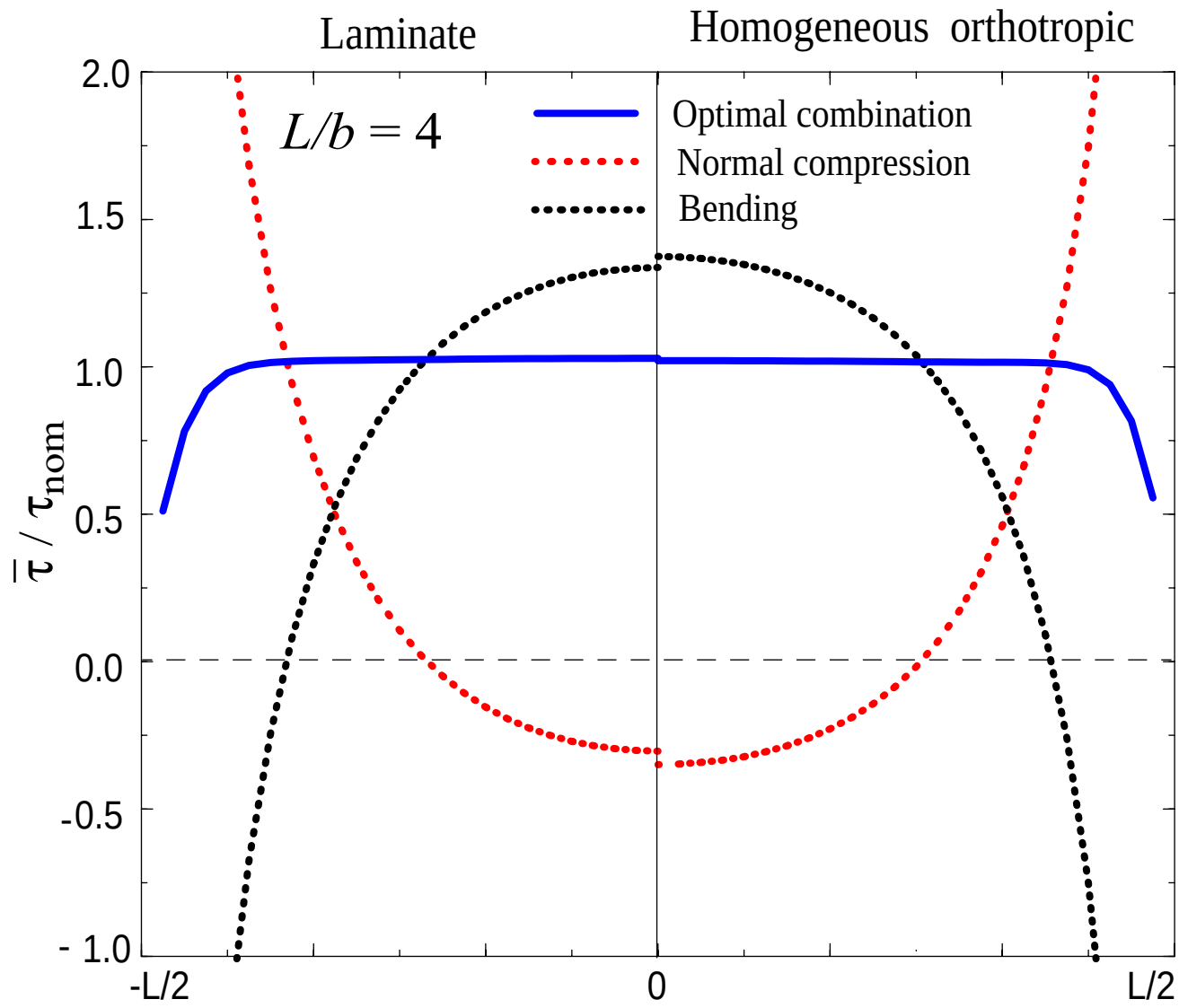
L/b	$\alpha_{eq.}$	α_{FE}^{Ortho}	α_{FE}^{Lam}
1	48.59°	48.52°	50.10°
2	34.44°	34.48°	35.22°
3	30.08°	30.06°	30.53°
4	28.85°	28.81°	29.19°

Isotropic material:

L/b	$\alpha_{eq.}$	α_{FE}^{iso}
1	46.14°	45.94°
2	33.36°	33.16°
3	29.38°	29.20°
4	28.29°	28.13°

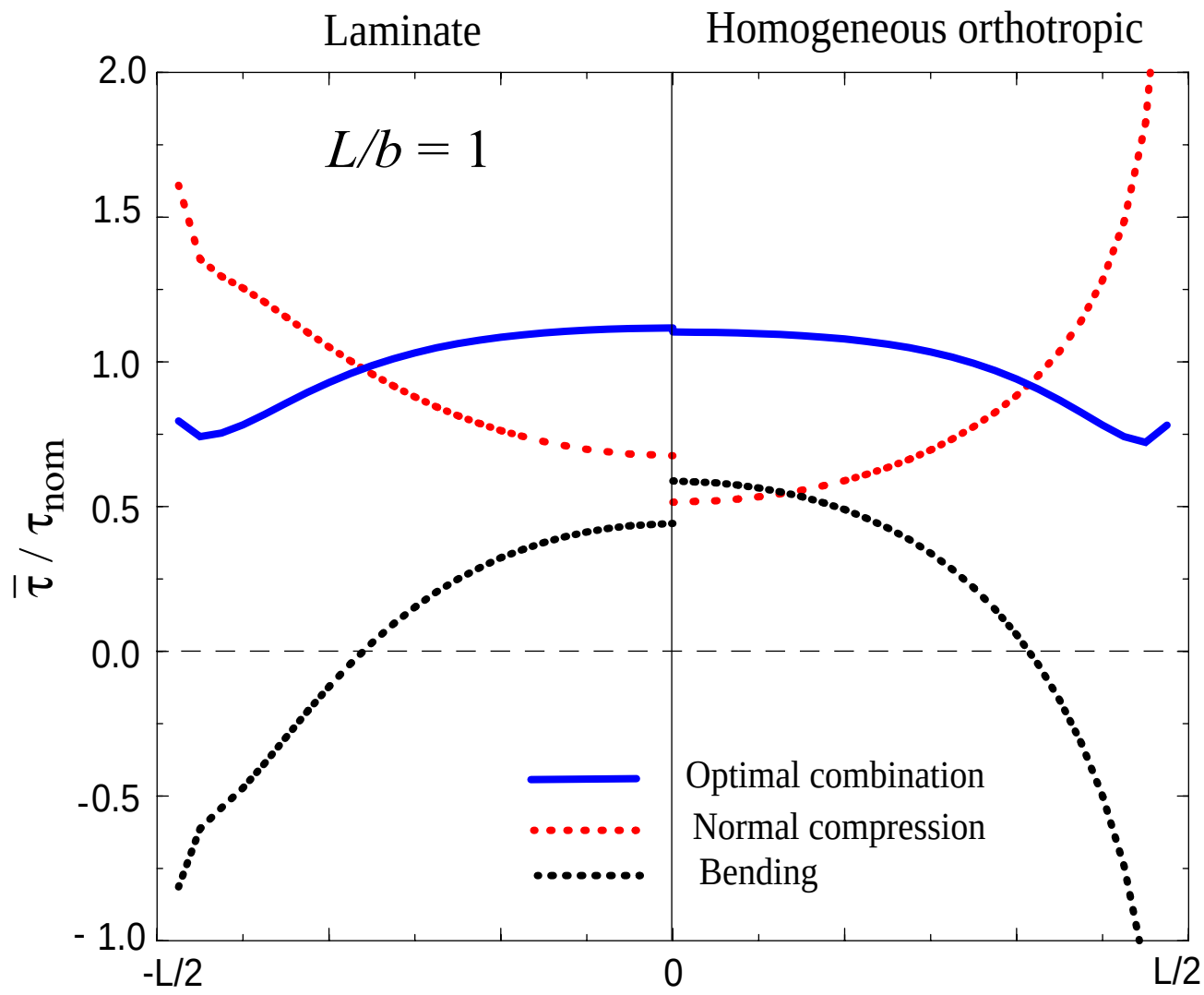
FE - analysis: Stress distributions

for optimally adjusted α



FE - analysis: Stress distributions

for optimally adjusted α



IDNS Test: Conclusions

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- Uses **inherent drawbacks** of poor-performing (DNC-) specimen to eliminate these, by applying them **twice** (with **opposite sign**)
- **Two loadsets** on the specimen are created by a **pair of holders**
- **Proportions** between loadsets are adjusted by **inclining** holders, α
- Proper proportions **fulfill target condition**: $K_{\mathrm{I}}^{\mathrm{tot}} = K_{\mathrm{I}}^{N} + K_{\mathrm{I}}^{M} = 0$
- Which is accomplished for α given by a **simple equation**
- Correct α includes specimen **geometry** and material **orthotropy**
- FE-analysis proves simple **equation** to be **very accurate**
- FE-results show that (almost) **uniform stresses** are achieved
- **Insensitive** to internal material microstructure (individual **layers**)

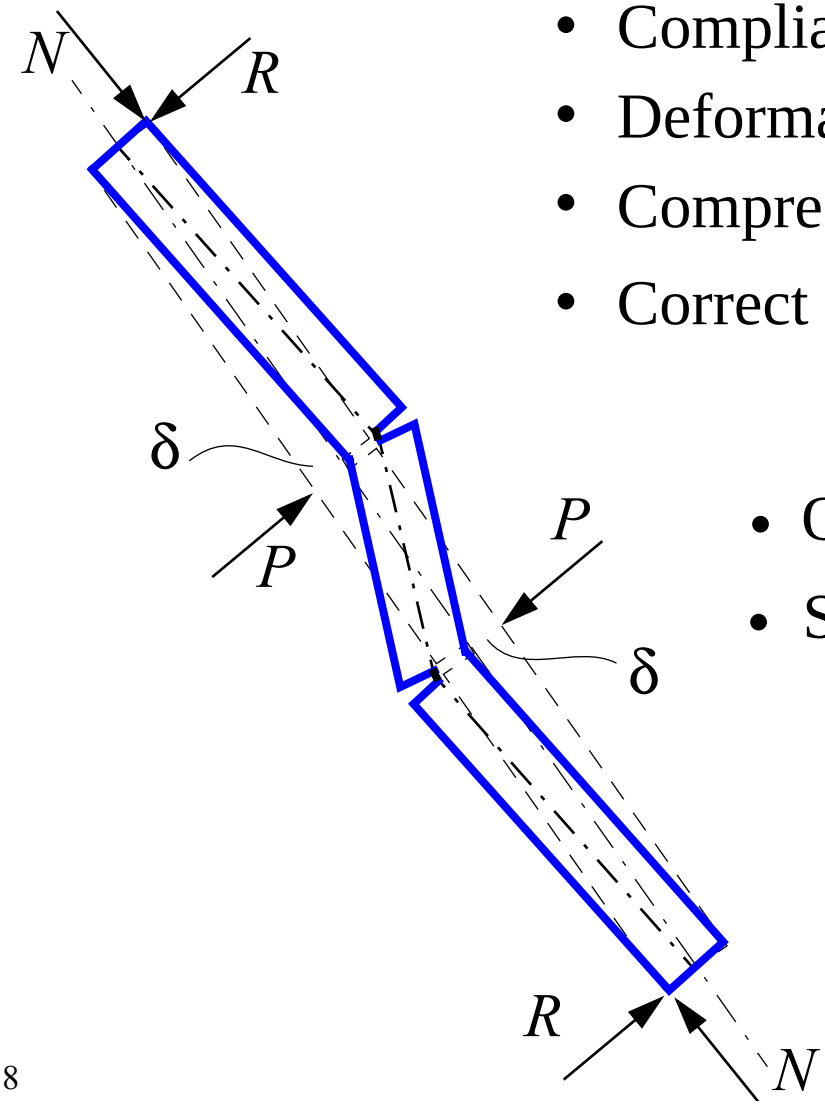
IDNS Test: Conclusions

Further issues

- Test method is **sensitive to deviations** from nominal conditions
- Equation for correct based on **non-deforming** specimens
- In practice: specimen **deforms**, conditions slightly **alter** during test
- Short notch distances: minor **mode-II** component present
- **Long** notch distances give the **most uniform** stress fields, but
- Experimentally, **short** notch distances give **best ILSS results**
- Short notch distances require **higher** α and thus **normal stresses**
- **Dependence** on notch distance **much lower** than for **DNC**-test
- **Feasability** of achieving $K_{\mathrm{I}}^{\mathrm{tot}} = 0$ must be **studied experimentally**

Deforming specimen

Exaggerated deformation



- Compliant specimen deforms (in shear) when loaded
- Deformation alters conditions at notch during test
- Compressive loading mode amplifies non-linearity
- Correct proportions at peak load require inital $\alpha_{set} < \alpha$

- Optimal test set-up depends on shear strength
- Set-up and results depend on elastic properties

Other Shear Tests: Short 3-point Bending

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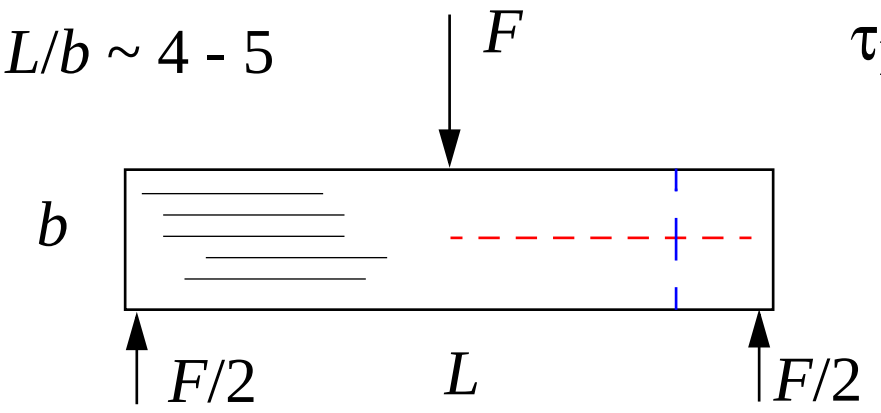
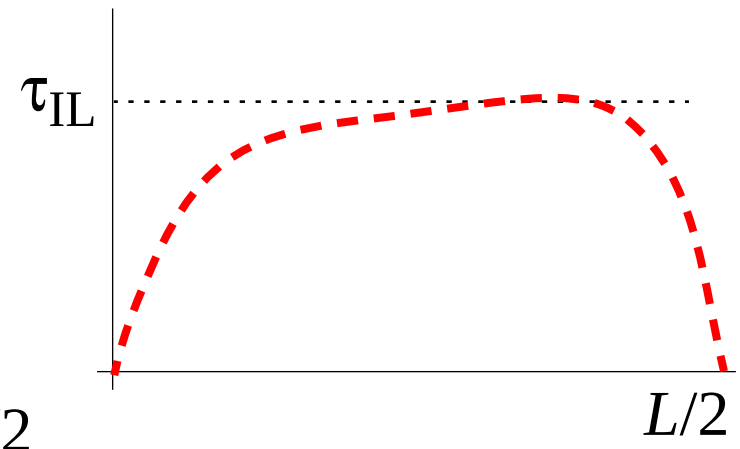
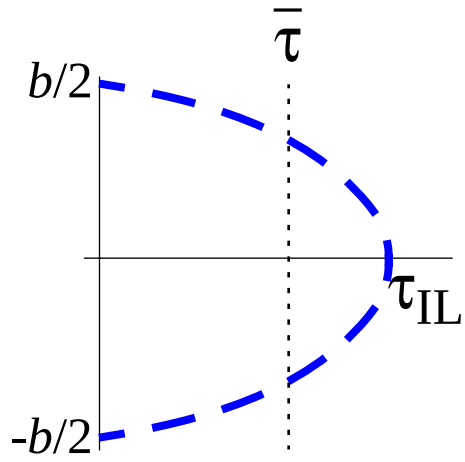
- **Calculates** interlaminar shear: $\tau_{IL} = 1.5\,\bar{\tau}$ (elastic conditions)
- Relies on **long slender** beam (conditions far from loading points)
- Shear failure requires **short** beams: **Distorted** stress fields
- Distortion amplified by **anisotropy** (corresponds to even shorter)
- **Non-linear** material (close to peak stress) gives **erroneous** stresses

Short beam:
$L/b \sim 4 - 5$







Other Shear Tests: Iosipescu Test

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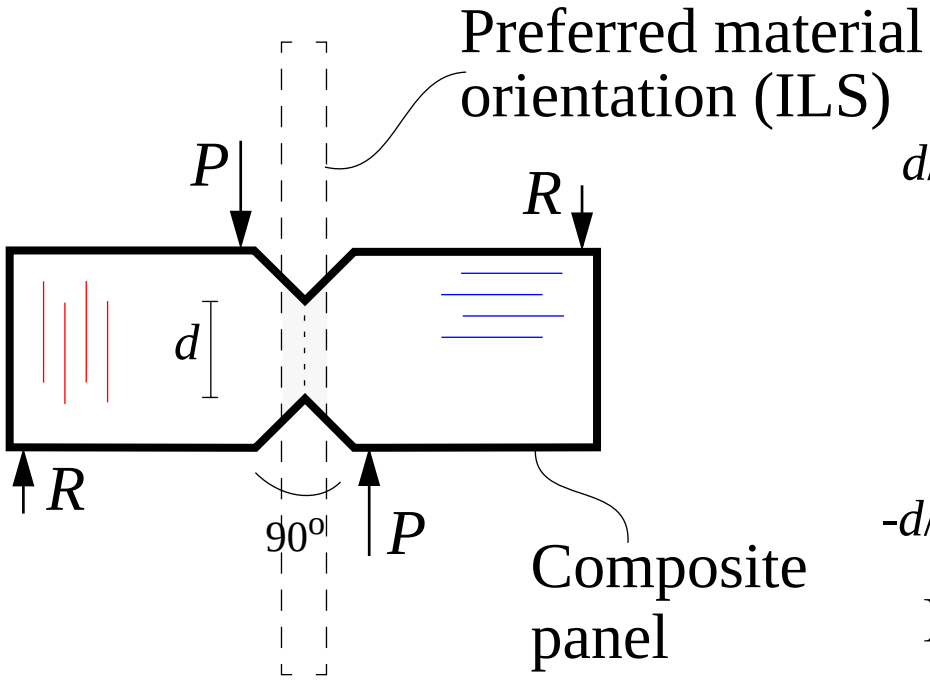
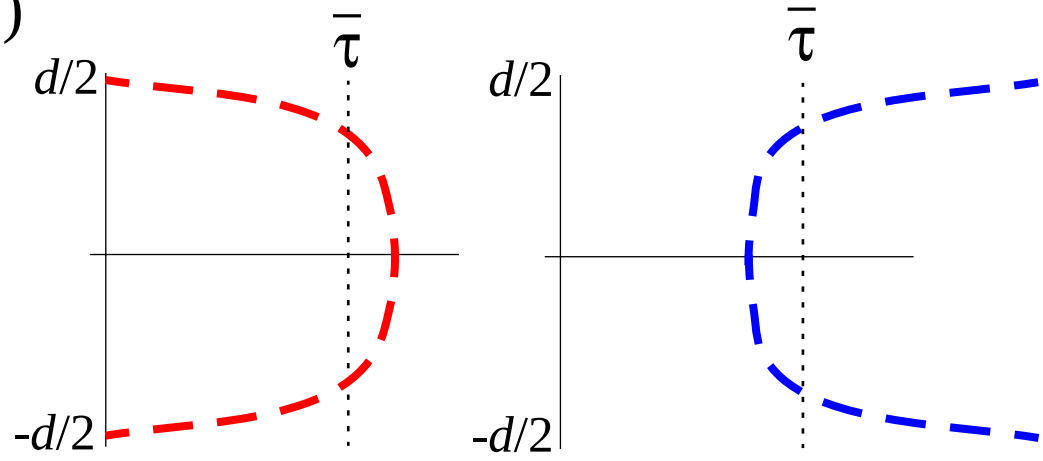
- Creates **true shear stresses** in test region
- Suitable for (**in plane**) panel properties (**not through thickness**)
- **Difficult** to create Iosipescu specimen for **true interlaminar** shear
- **Non uniform** shear stress fields, depend on material **anisotropy**
- Results depend on **material orientation**, interpretation?





Fibers along or across test region

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Thank You !