Influence of Geometrical Imperfections on Local Buckling of GFRP Plates in Civil Engineering

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VARTM: All FRP structures with freedom of shape, size, thickness & layup ☺ … but prone to imperfections ☹

VARTM production of a beam (Robinson, 2008)

Bio-based FRP bridge in Friesland (2019)

Multidirectional (MD) laminates: Ex = Ey … Ex >> Ey

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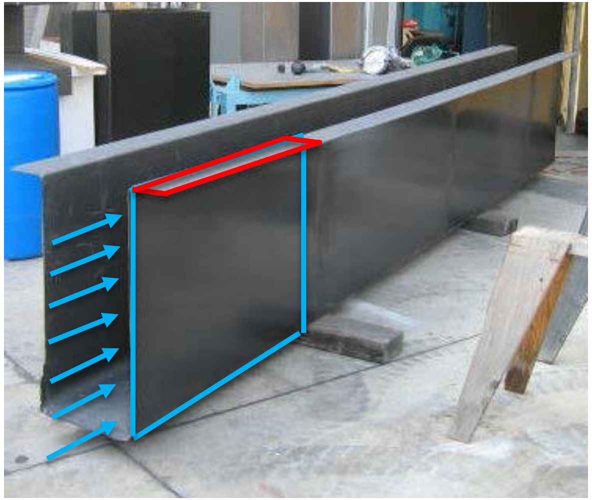
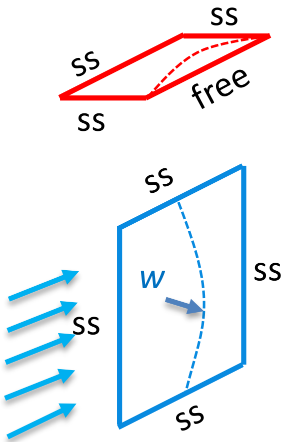
VARTM = Vacuum Assisted Resin Transfer Moulding (a.k.a. Vacuum Infusion)

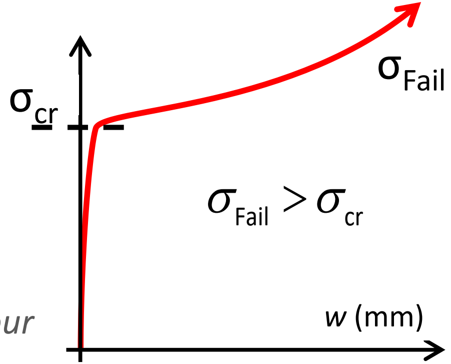
Current design verification workflow (EUR 27666EN, CUR96, …) excludes the influence of imperfections!





$$\sigma_{Ed} \leq \frac{\sigma_{cr} \cdot \eta_c}{\gamma_M}$$

$$\sigma_{cr} = \frac{\pi^2}{t \cdot b^2} \cdot \left[2\sqrt{D_{11} \cdot D_{22}} + 2 \cdot (D_{12} + 2 \cdot D_{66}) \right]$$



Assumption of stable post-buckling behaviour

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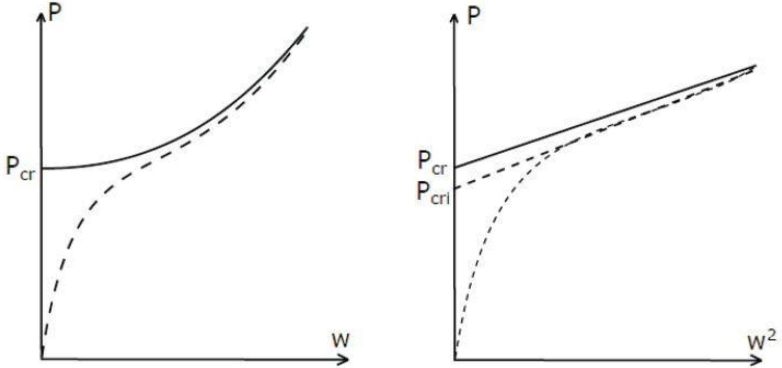
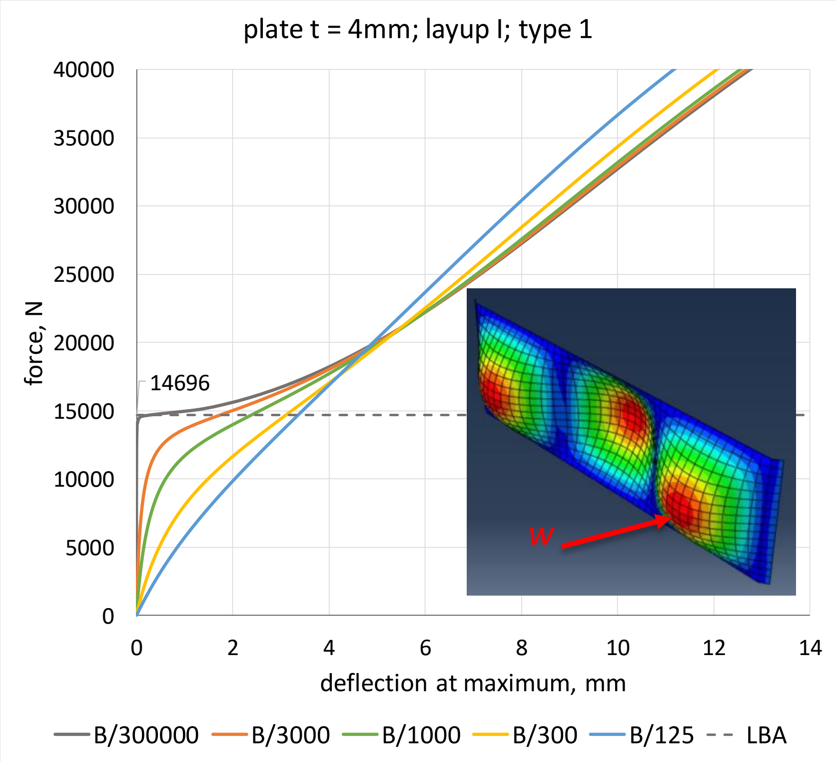
Prediction of critical stress is unreliable for plates with out-of-plane geometrical imperfections.



P-w² method: Czapski & Kubiak 2016)



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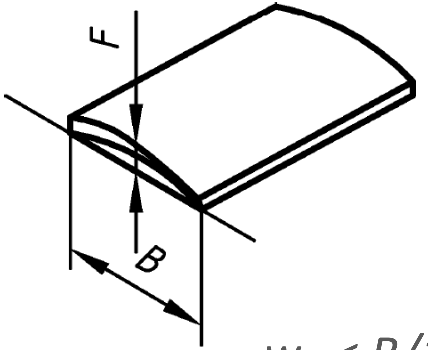
Imperfections specified for pultruded profiles might not be relevant for VARTM

Pultruded: EN 13706-2

Fabrication tolerances!



$w_0 < B/125$

VARTM: no standard!

Possible causes of imperfections:

- *Moulds*
- *Curing temperatures*
- *Shrinkage,*
- *Large slenderness,*
- *Various MD laminates*

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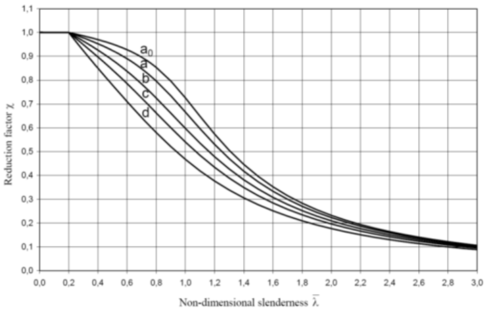
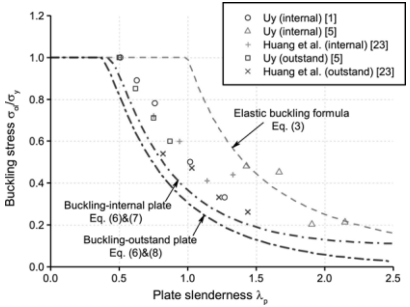
GOAL: Build a set of buckling curves based on equivalent geometric imperfections!



Examples: Steel profiles

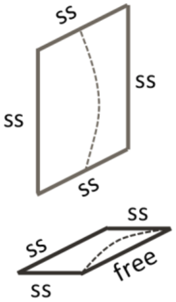
$$\chi = \frac{1}{\Phi + \sqrt{\Phi^2 - \bar{\lambda}^2}}$$

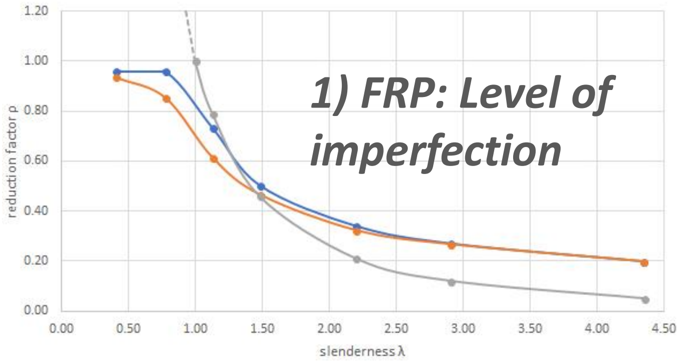


Steel plates

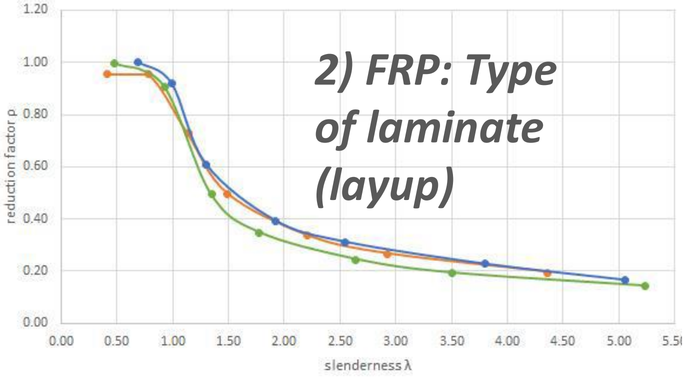
$$\rho = \frac{\bar{\lambda}_p - 0{,}055\,(3+\psi)}{\bar{\lambda}_p^2} \le 1{,}0$$

$$\rho = \frac{\bar{\lambda}_p - 0{,}188}{\bar{\lambda}_p^2} \le 1{,}0$$





1) FRP: Level of imperfection



2) FRP: Type of laminate (layup)

3) FRP: Boundary conditions

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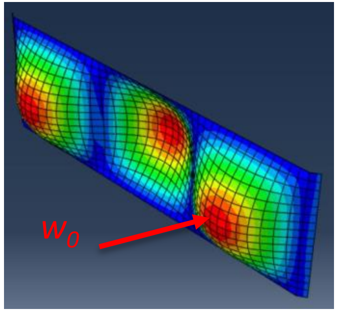
APPROACH: Non-linear buckling FEA to asses sensitivity of MD laminated plates to imperfections.

Imperfections



1st mode shape

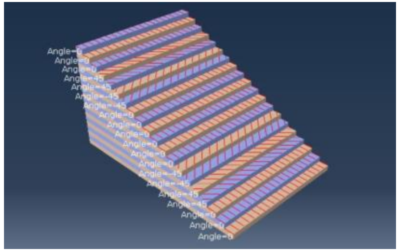
$w_0 = B/125 - B/1000$

high *low*

LBA

$\sigma_{cr} = ...$

Ply based material



E1, MPa	E2, MPa	G12, MPa	ν12
37200	11400	3400	0.29

+ Hashin damage model

f1t, MPa	f1c, MPa	f2t, MPa	f2c, MPa	f12, MPa
744	446.4	22.8	102.6	64.6

strength + fracture energies

MNA or CLT

strength: f_{ult} *= ...e.g. 229 MPa*

GMNIA

$f_{fail} = ...$

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CASE: MD laminated plate with simply supported boundary conditions in a range of slenderness

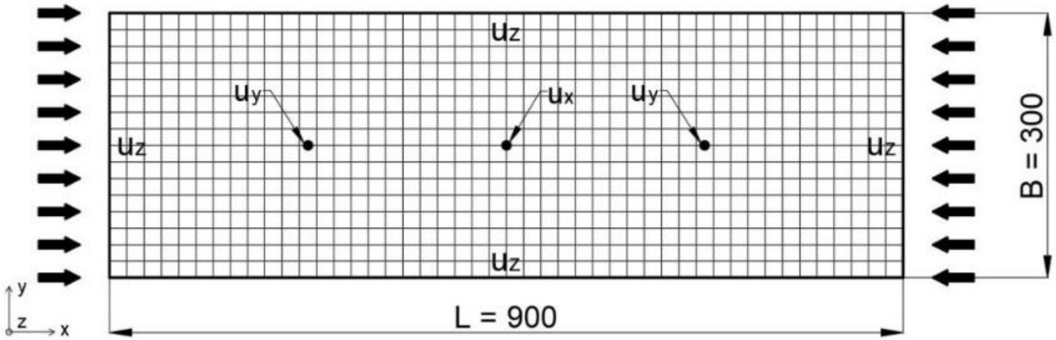
MD laminate composition:

$[0_2/45_2/-45_2/90_2/0_2]_s$

$E_x = 22.56$ GPa

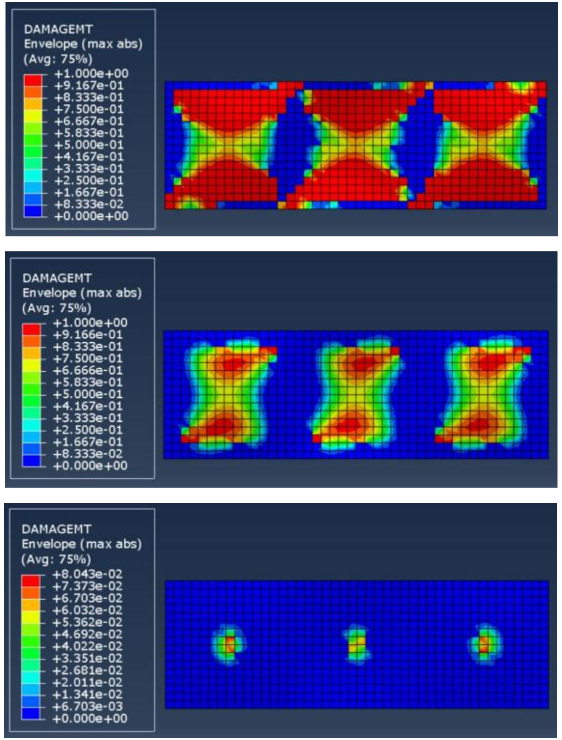
→ =1.27

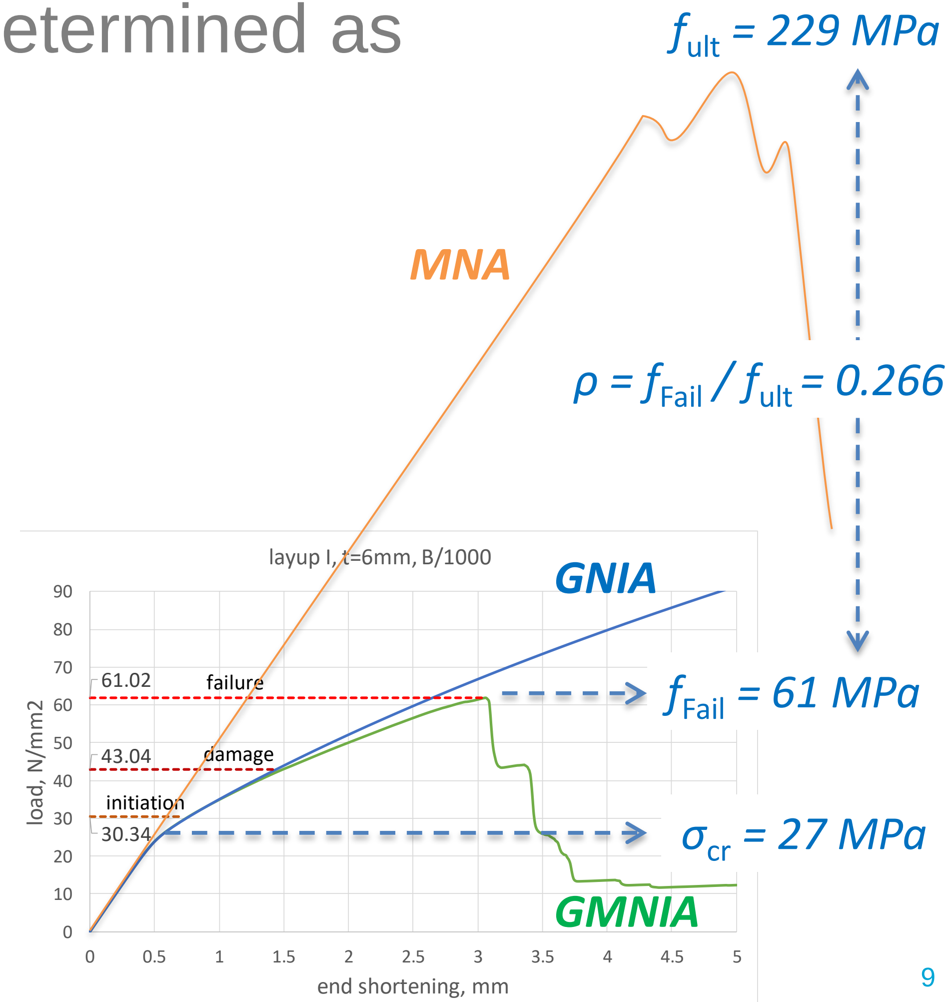
$E_y = 17.71$ GPa



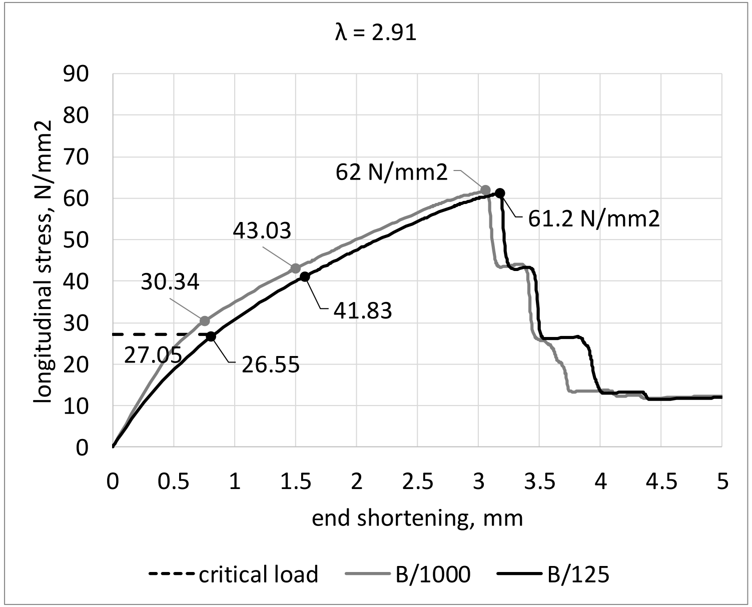
t = 4 ÷ 54 mm → **λ ≈ 0.5 ÷ 4.0**

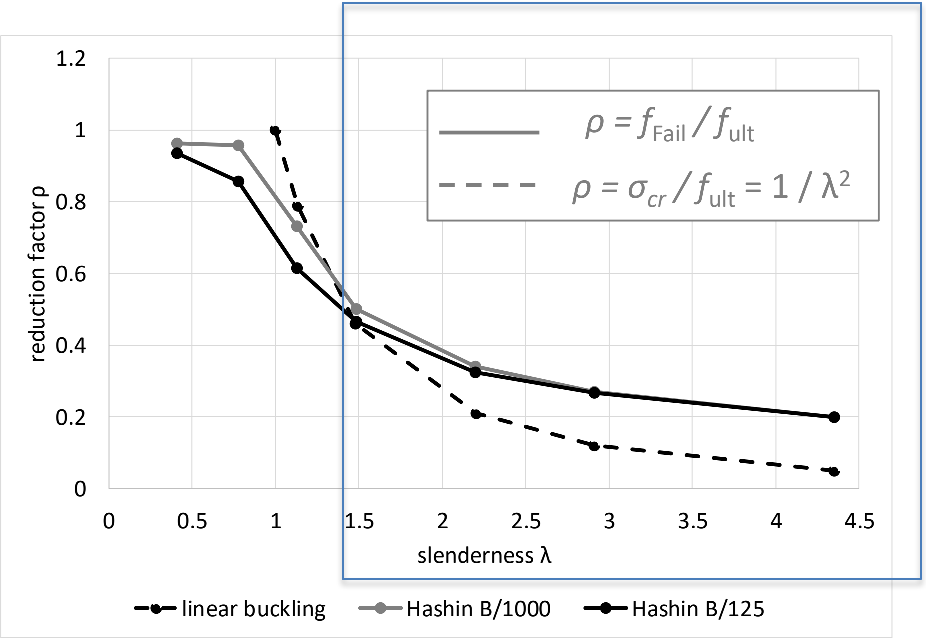
The buckling resistance is determined as ultimate load in GMNIA





Influence of imperfections is relatively small for slender (thin) plates λ > 1.5!





Conservative design by: $\sigma_{Ed} \leq \frac{\sigma_{cr} \cdot \eta_c}{\gamma_M}$

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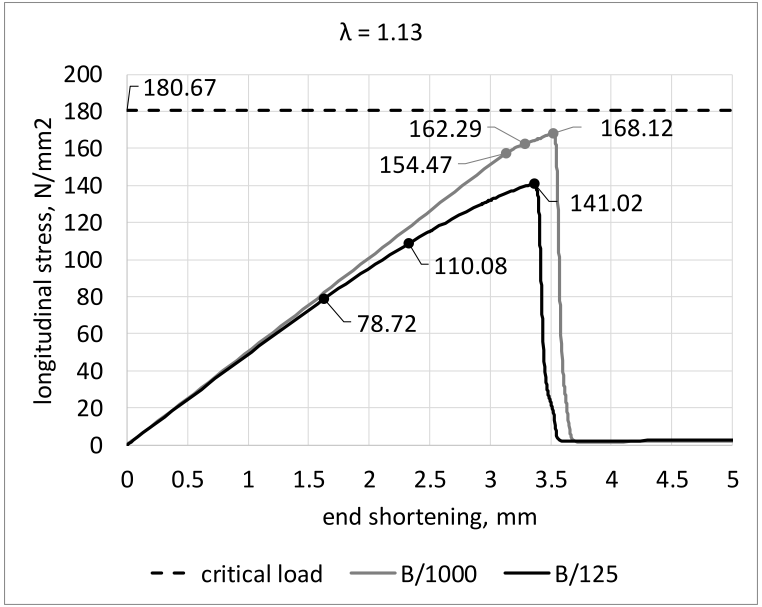
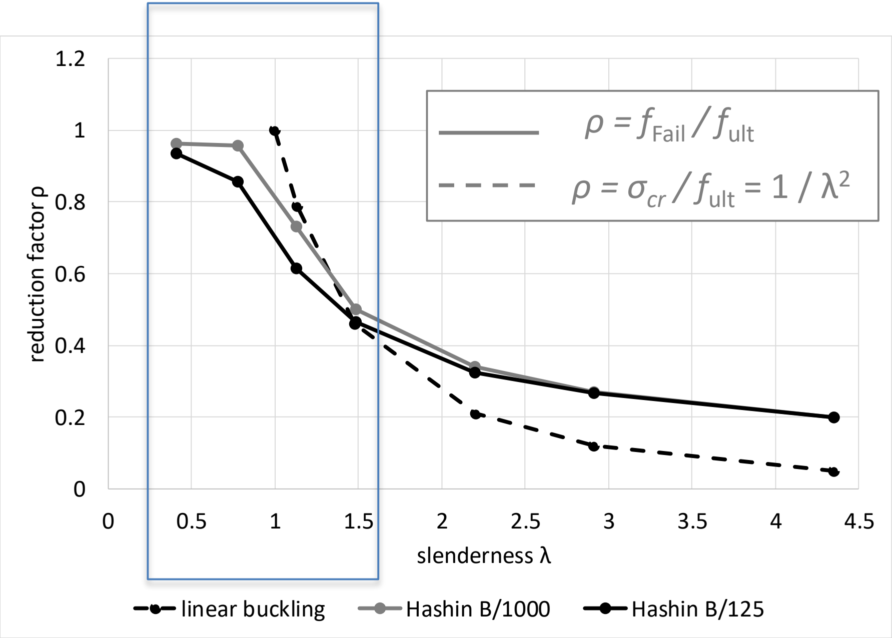
Stocky (thick) plates with λ < 1.5 unsafe design by critical stress with significant influence of imperfections!





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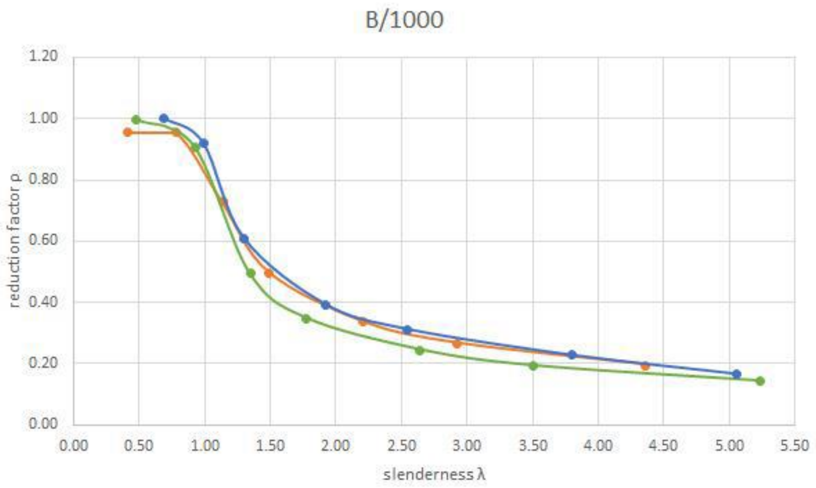
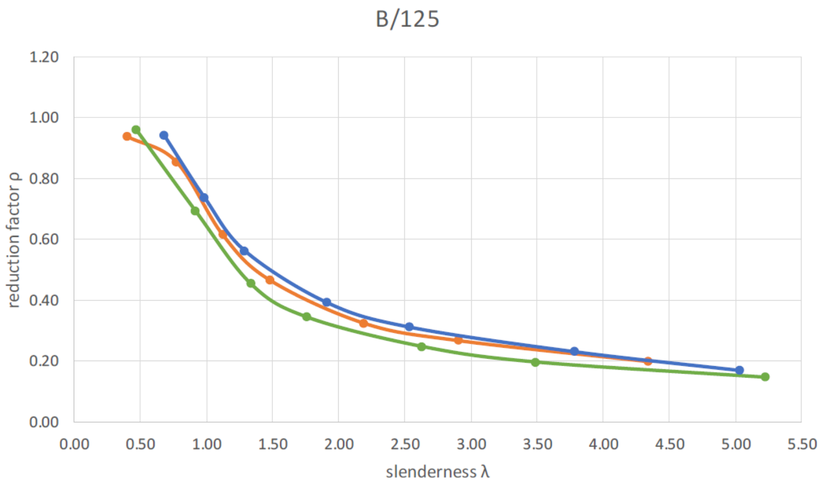
CONCLUSION: *Prediction of buckling resistance of FRP plates must include imperfections!*

- *Imperfections of B/125 result in up to 15% additional reduction on stocky plates.*
- *Resistance of stocky plates is up to 20% overestimated by critical stress approach.*
- *x2 conservative design of slender plates ($\lambda > 2.5$) based on critical stresses approach.*

- *Buckling curves approach is feasible to cover aspects of:*
  - *Different laminates*
  - *Different boundary conditions* <- *experiment validation*
  - *Level of (equivalent) geometric imperfections* <- *measurements*

OUTLOOK: Variation of orthotropy (layup) results in 20% variation of reduction factor





layup III: $E_{cx}/E_{cy} = 1.0; D_{11}/D_{22} = 1.45; f_{ult} = 182.78\ N/mm^2$

layup I: $E_{cx}/E_{cy} = 1.27; D_{11}/D_{22} = 1.74; f_{ult} = 229.09\ N/mm^2$

layup II: $E_{cx}/E_{cy} = 1.80; D_{11}/D_{22} = 2.41; f_{ult} = 298.59\ N/mm^2$

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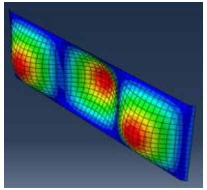
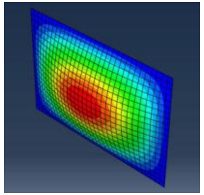
VALIDATION: The results are independent of aspect ratio, as long as shape and critical stress of the 1st critical mode shape is taken!

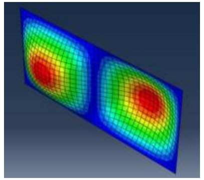
300 x 900 mm;
AR = 3.0
λ = 0.4 – 4.4

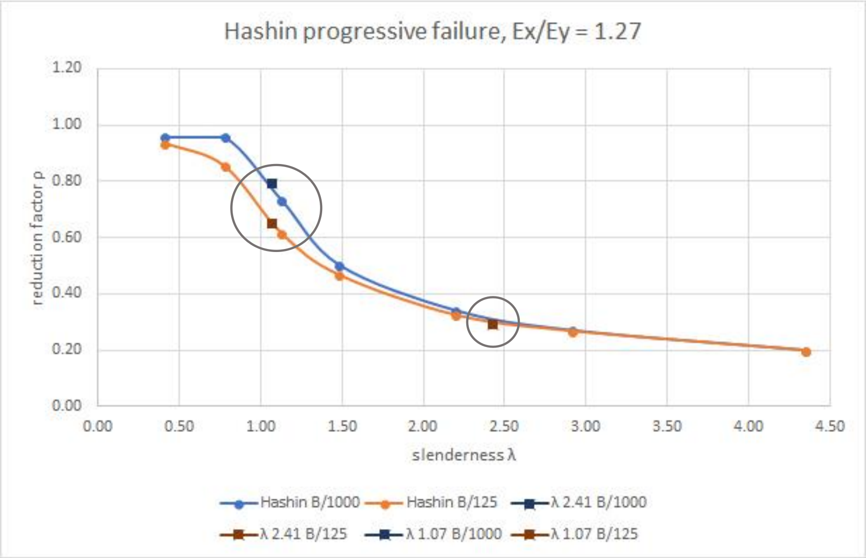


400 x 600 mm;
AR = 1.5
λ = 2.41



700 x 1600 mm;
AR = 2.29
λ = 1.07





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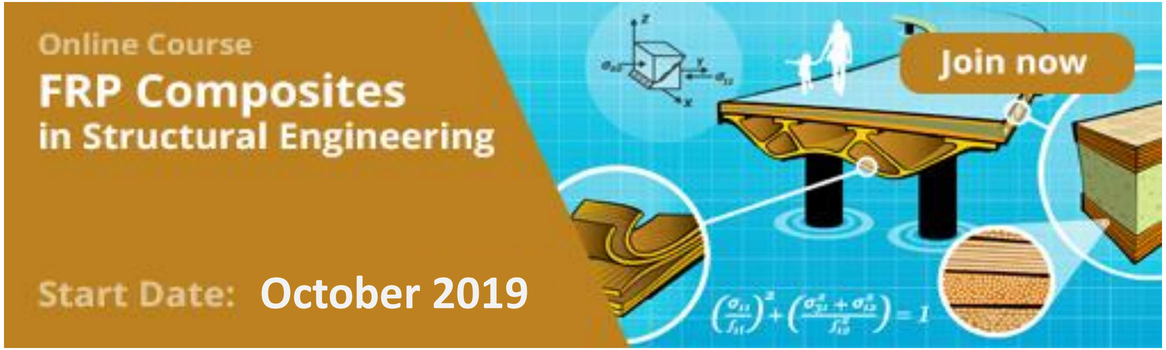

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