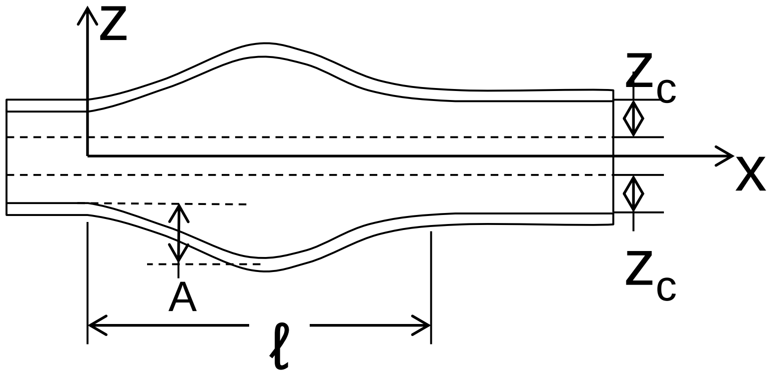
Symmetric wrinkling

- the derivation so far assumed that the core is sufficiently thick so that $z_c \le t_c/2$



- if (5.5.3.2.13) gives $z_c > t_c/2$, then

$$z_c = \frac{t_c}{2} \qquad (5.5.3.2.13a)$$

- substituting in (5.5.3.2.11)

$$\ell = \frac{\pi}{24^{1/4}} \left(\frac{E_f}{E_c} t_f^{\,3} t_c \right)^{1/4} \qquad (5.5.3.2.14a)$$

Symmetric wrinkling

- and substituting for z_c and ℓ in (5.5.3.2.10),

$$N_{xwr} = 0.816\sqrt{\frac{E_f E_c t_f^{\,3}}{t_c} + G_{xz}\frac{t_c}{6}} \qquad (5.5.3.2.15a)$$

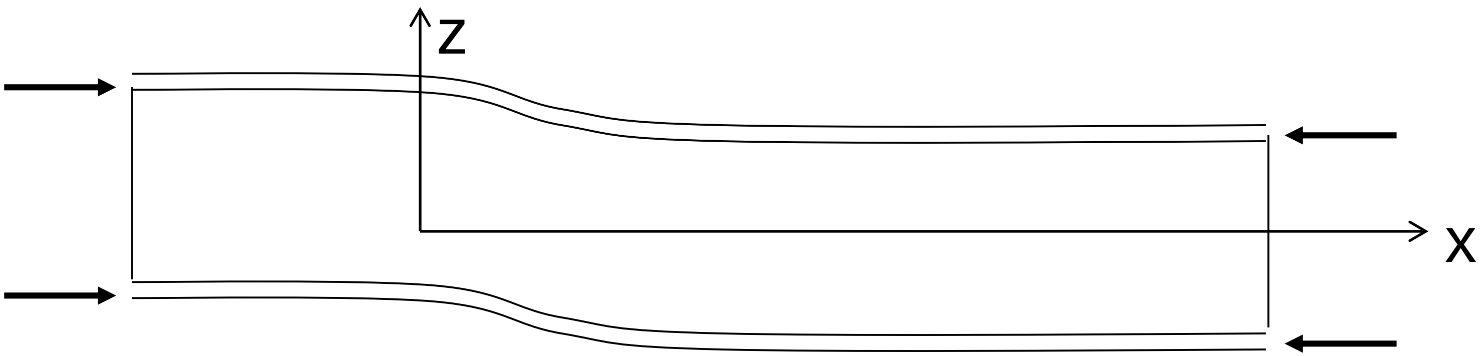
- to find the condition for the full-depth of the core being “active” (z_c=t_c/2) use eq. (5.5.3.2.13):

$$t_c < 1.817 t_f \left(\frac{E_f E_c}{G_{xz}^{\,2}}\right)^{1/3} \qquad (5.5.3.2.16)$$

- if (5.5.3.2.16) is valid, then z_c=t_c/2 and eqs (5.5.3.2.14a) and (5.5.3.2.15a) are valid; otherwise, (5.5.3.2.13)-(5.5.3.2.15) are valid

Anti-symmetric wrinkling

- in an analogous fashion but with different starting assumption for w(x,z), the following expressions are obtained for anti-symmetric wrinkling[1,2]



$$N_{xwr} = 0.51 t_f \left(E_f E_c G_{xz}\right)^{1/3} + \frac{G_{xz} t_c}{3}$$

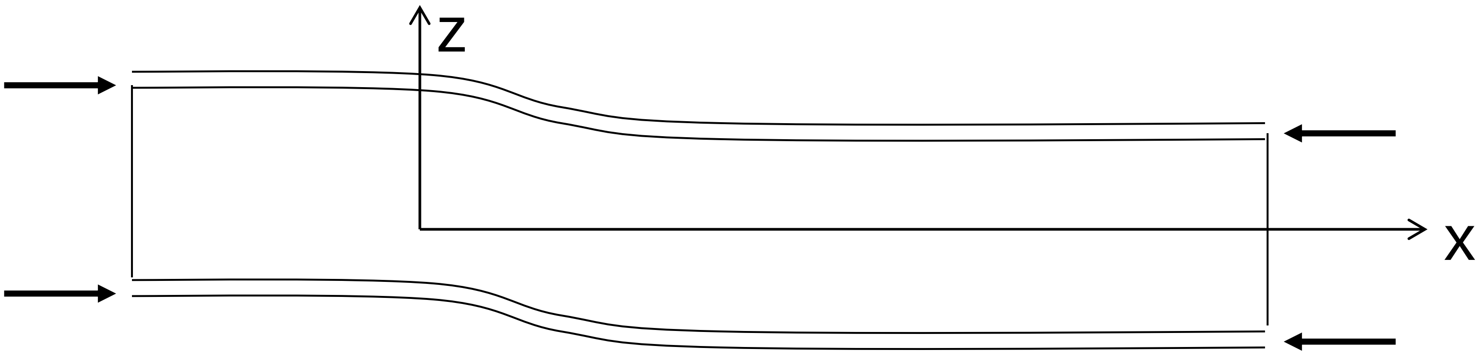
$$\ell = 2.15 t_f \left(\frac{E_f^{\ 2}}{E_c G_{xz}}\right)^{1/6} \qquad for \quad t_c \geq 3 t_f \left(\frac{E_f E_c}{G_{xz}^{\ 2}}\right)^{1/3} \qquad (5.5.3.2.17)$$

$$z_c = \frac{3}{2} t_f \left(\frac{E_f E_c}{G_{xz}^{\ 2}}\right)^{1/3}$$

(1) Hoff, N.J.,Mautner, S.E., “The Buckling of Sandwich-Type Panels”, J Aeronautical Sciences, July 1945, pp 285-297

(2) Vadakke, V., and Carlsson, L.A., “Experimental Investigation of Compression Failure Mechanisms of Composite Faced Foam Core Sandwich Specimens”, J. Sandwich Structures & Materials, 6, 2004, pp. 327-342

Anti-symmetric wrinkling (cont'd)



$$N_{xwr} = 0.59 t_f^{3/2} \sqrt{\frac{E_f E_c}{t_c}} + 0.378 G_{xz} t_c$$

$$\ell = 1.67 t_f \left(\frac{E_f t_c}{E_c t_f} \right)^{1/4} \qquad for \quad t_c < 3 t_f \left(\frac{E_f E_c}{G_{xz}} \right)^{1/3} \qquad (5.5.3.2.17a)$$

Wrinkling – comparisons with FE predictions

- the previous analysis for wrinkling assumed perfectly flat facesheets; in practice, the facesheets are wavy unless they are pre-cured and then bonded on the facesheet; for this reason, test results with flat facesheets are hard to come by and of little practical interest since facesheets are, typically, co-cured with the core as part of the same cure cycle.

- therefore, the easiest comparison is with a detailed FE model

Wrinkling – Comparison with FE predictions[1]

- facesheet: (0/90)/(±45)$_2$/(0/90) plain weave fabric with thickness 0.76 mm
- core thickness= 25.4 mm (properties shown below)

E_c (MPa)	G_{xz} (MPa)	N_{xwr}/t_f (MPa) present	N_{xwr}/t_f (MPa) FE	Δ%	ℓ (mm) present	ℓ (mm) FE	Δ%
133	42	646	658	**-1.8**	11.3	11.4	**-0.9**
266	42	842	1033	**-18.5**	9.5	8.9	**+6.7**
133	84	808	821	**-1.6**	10.6	13.2	**-19.7**

(1) Kassapoglou, C., Fantle, S.C., and Chou, J.C., "Wrinkling of Composite Sandwich Structures Under Compression", J Composites Technology and Research, 17, 1995, pp 308-316.

Wrinkling – Some points

• the discussion so far did not explicitly account for the fact that the facesheet is composite; only the value of E_f appropriately calculated would bring composites in the picture

• some researchers have explicitly included composite facesheets in the derivation; for example, for symmetric wrinkling the wrinkling load expression is[1]:

$$N_{xwr} = \underbrace{\frac{\pi^2}{a^2}\left[(D_{11})_f m^2 + 2\left((D_{12})_f + 2(D_{66})_f\right)\left(\frac{a}{b}\right)^2 + \frac{(D_{22})_f}{m^2}\left(\frac{a}{b}\right)^4\right]}_{\text{facesheet buckling load}} + \underbrace{\frac{2E_c a^2}{m^2 \pi^2 t_c}}_{\text{core (elastic foundation) contribution}}$$

Note the similarity with our "generic" eq. (5.5.3.2.10) and the fact that the contribution from core shear is missing here!

(1) Pearce, T.R.A. and Webber, J.P.H., "Buckling of Sandwich Panels with Laminated Face Plates", Aeronautical Quarterly, 23, 1972, pp. 148-160

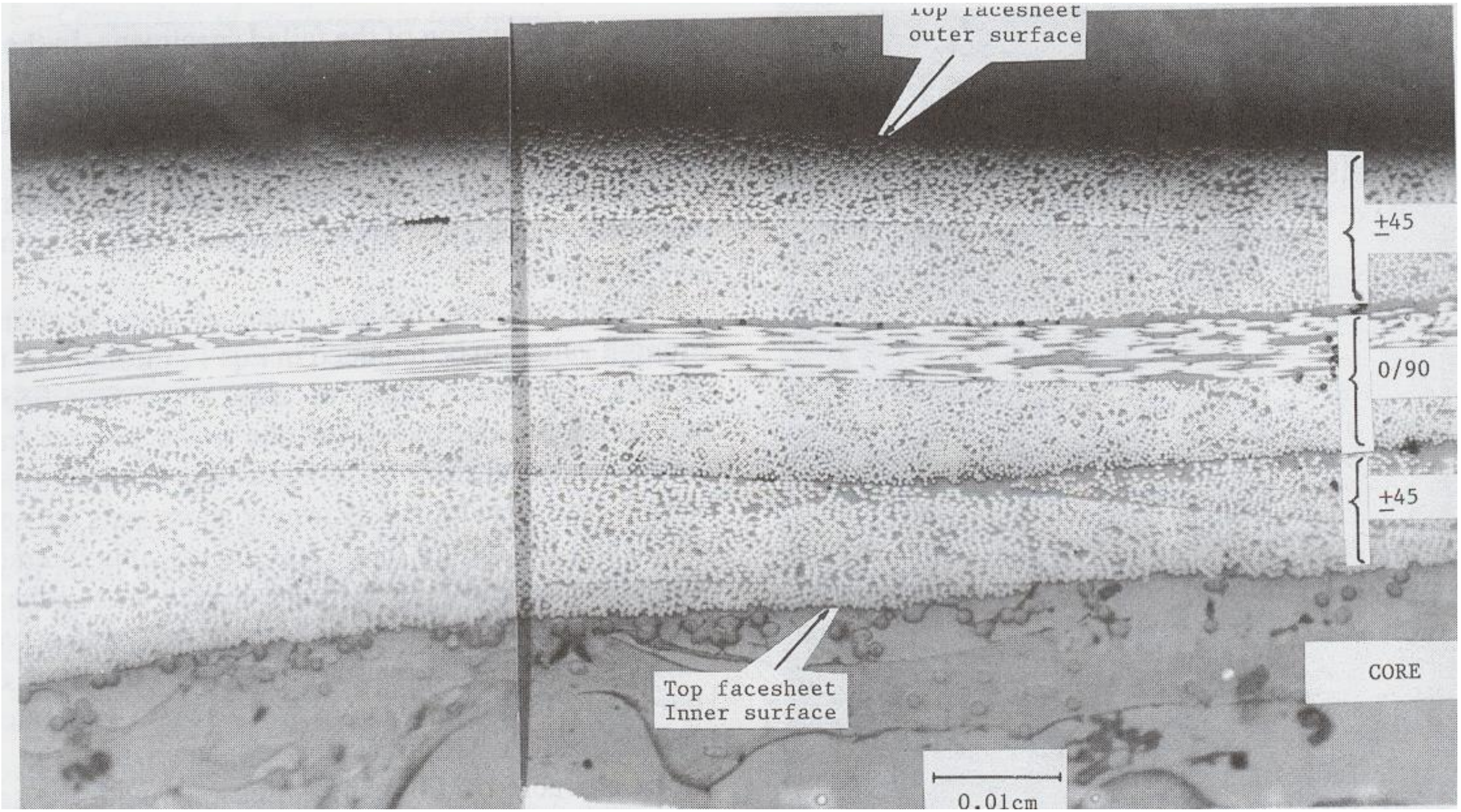
Wrinkling – Some Points

- to paraphrase P.A. Lagace, “there are as many wrinkling equations as there are researchers in the field”; it is a matter of preference which equations one uses and what knockdown factors are appropriate to replace the numerical coefficients

- a comparison of a variety of methods with test results can be found in: Dobyns, A., “Correlation of Sandwich Facesheet Wrinkling Test Results with Several Analysis Methods”, 51st AHS Forum, Ft Worth, TX, May 9-11, 1995

- the main conclusion is that the presence of facesheet waviness makes these methods unreliable (unless properly “adjusted”)

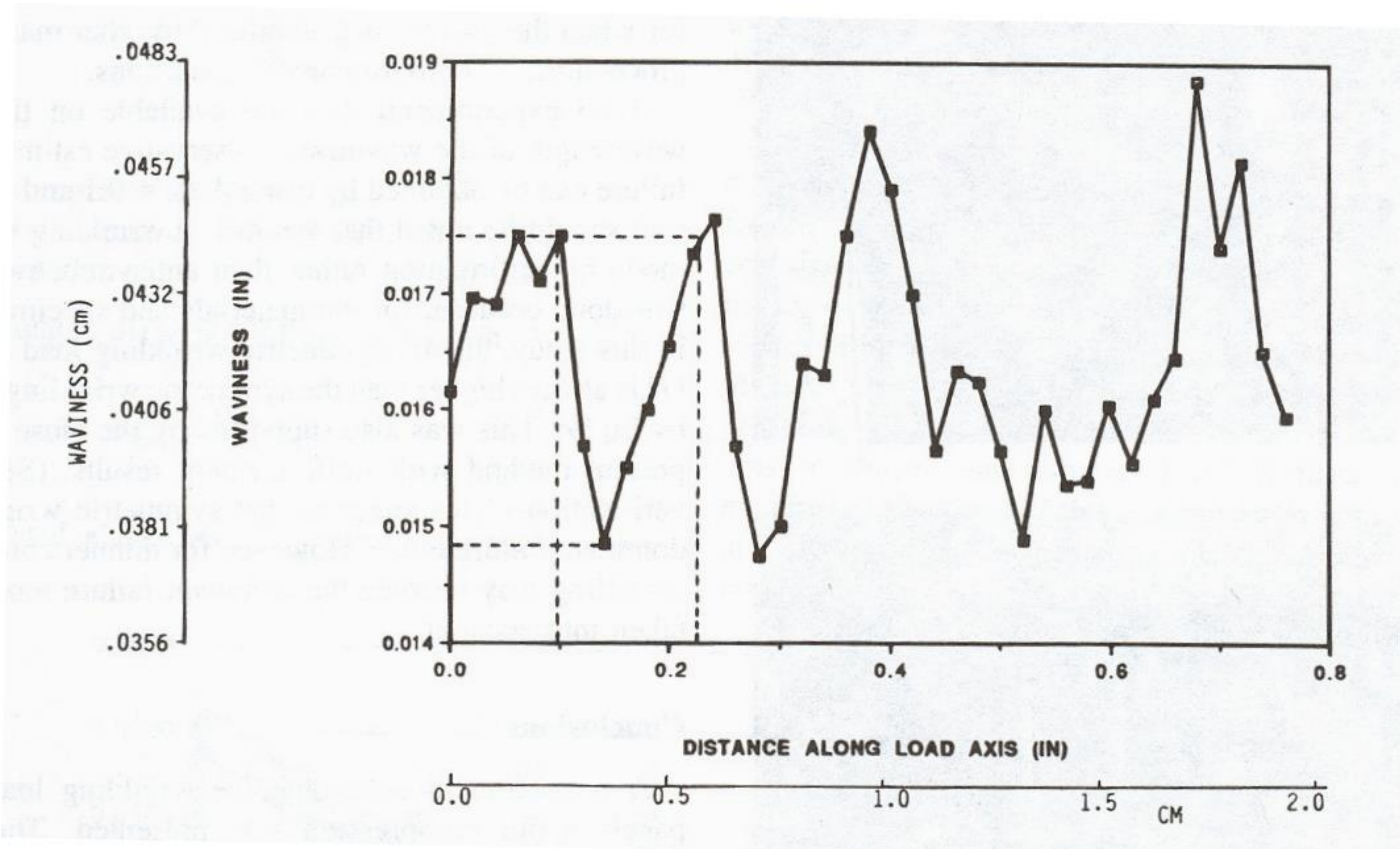
Wrinkling – Effect of Waviness



portion of upper facesheet and core at 200X magnification

from: Kassapoglou, C., Fantle, S.C., and Chou, J.C., “Wrinkling of Composite Sandwich Structures Under Compression”, J Composites Technology and Research, 17, 1995, pp 308-316

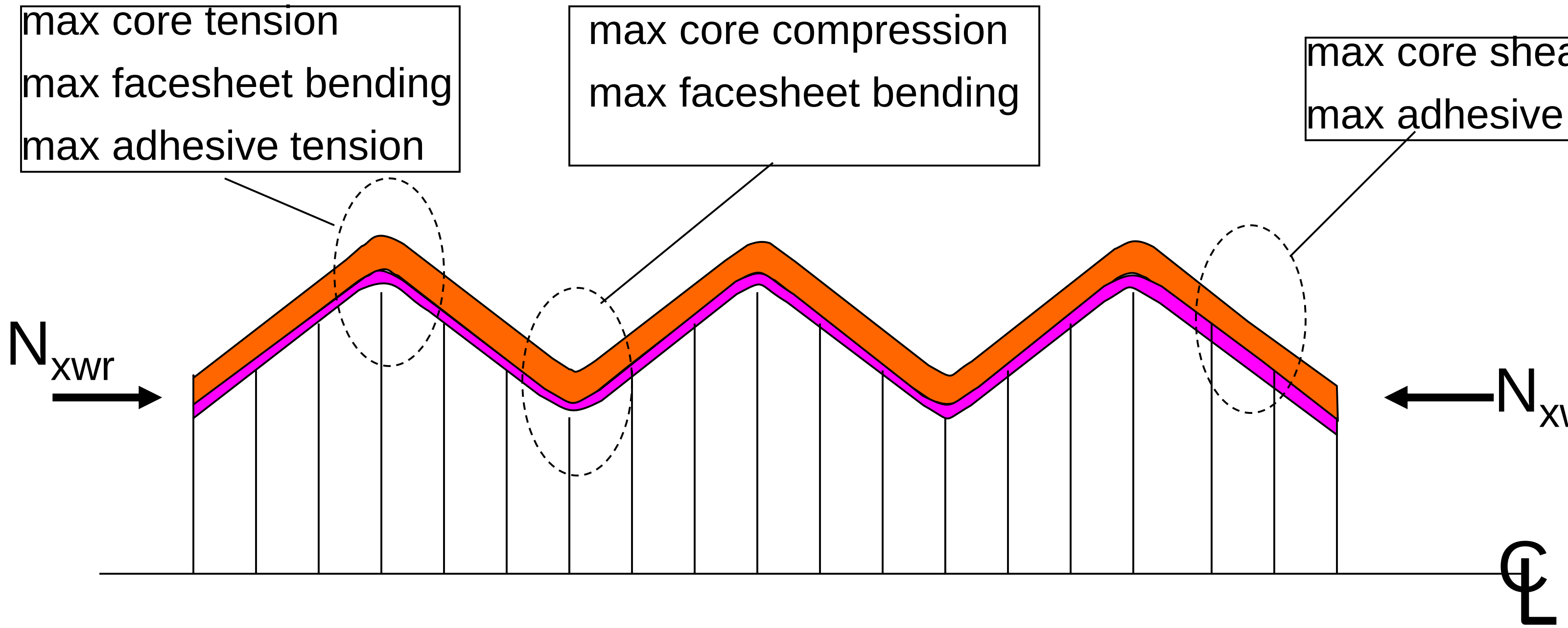
Wrinkling – Effect of Waviness



- measured waviness from Kassapoglou et al

Wrinkling – Effect of waviness

- assuming waviness is periodic of known amplitude and wavelength one can solve for the facesheet deflections under compression[1]



(1) Kassapoglou, C., Fantle, S.C., and Chou, J.C., “Wrinkling of Composite Sandwich Structures Under Compression”, J Composites Technology and Research, 17, 1995, pp 308-316

Wrinkling – Using waviness to predict failure

- measure amplitude and wavelength or determine conservative values
- use bending modulus for the facesheet since the facesheet is predominantly in bending
- apply equations for the different failure modes
  - facesheet bending
  - adhesive shear or tension
  - core tension, compression or shear

Wrinkling – Using waviness to predict failure

Facesheet	Core	Predicted wr. stress (MPa)	Test wr. stress (MPa)	Δ%
(±45)/(0/90)	Nomex HRH 10-1/8-3.0	295	313	**-5.8**
(±45)/(0/90)/ (±45)	Nomex HRH 10-1/8-3.0	264	297	**-11.2**
(±45)/$(0/90)_2$/ (±45)	Nomex HRH 10-1/8-3.0	426	337	**+26.4**
(±45)/(0/90)	Phenolic HFT 3/16-3.0	344	350	**-1.8**
(±45)/(0/90)/ (±45)	Phenolic HFT 3/16-3.0	255	349	**-26.9**
(±45)/$(0/90)_2$/ (±45)	Phenolic HFT 3/16-3.0	309	382	**-19.0**
(±45)/(0/90)/ (±45)	Korex 1/8-3.0	246	365	**-32.7**

What does all this mean?

- methods not very reliable; require use of judgement, or
- use method of preference with appropriate knockdown factor
- recommended for design[1]) (<u>without</u> need to check if full-depth of core is effective unless t_c<5mm):

$$N_{xwr} = \underbrace{0.43}t_f \left(E_f E_c G_{xz}\right)^{1/3}$$ (symmetric wrinkling) (5.5.3.2.18)

compare with 0.91 of eq. (5.5.3.2.15)

$$N_{xwr} = \underbrace{0.33}t_f E_f \sqrt{\frac{E_c}{E_f}\frac{t_f}{t_c}}$$

note core shear modulus is not present

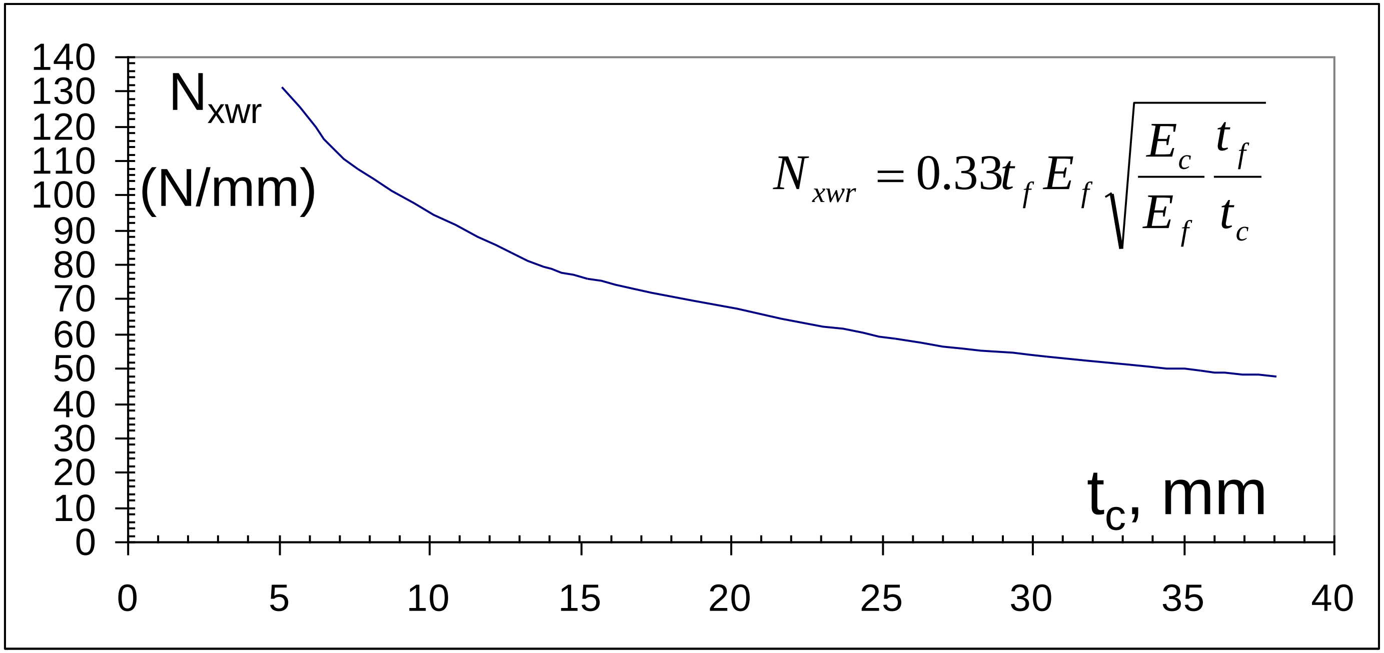
(anti-symmetric wrinkling) (5.5.3.2.19)

compare with 0.82 of eq. (5.5.3.2.17)

(1) for 0.43 factor, see Bruhn, E.F., “Analysis and Design of Flight Vehicle Structures”, S.R. Jacobs & Assoc, Indianapolis, IN, 1973, section C12.10.3;

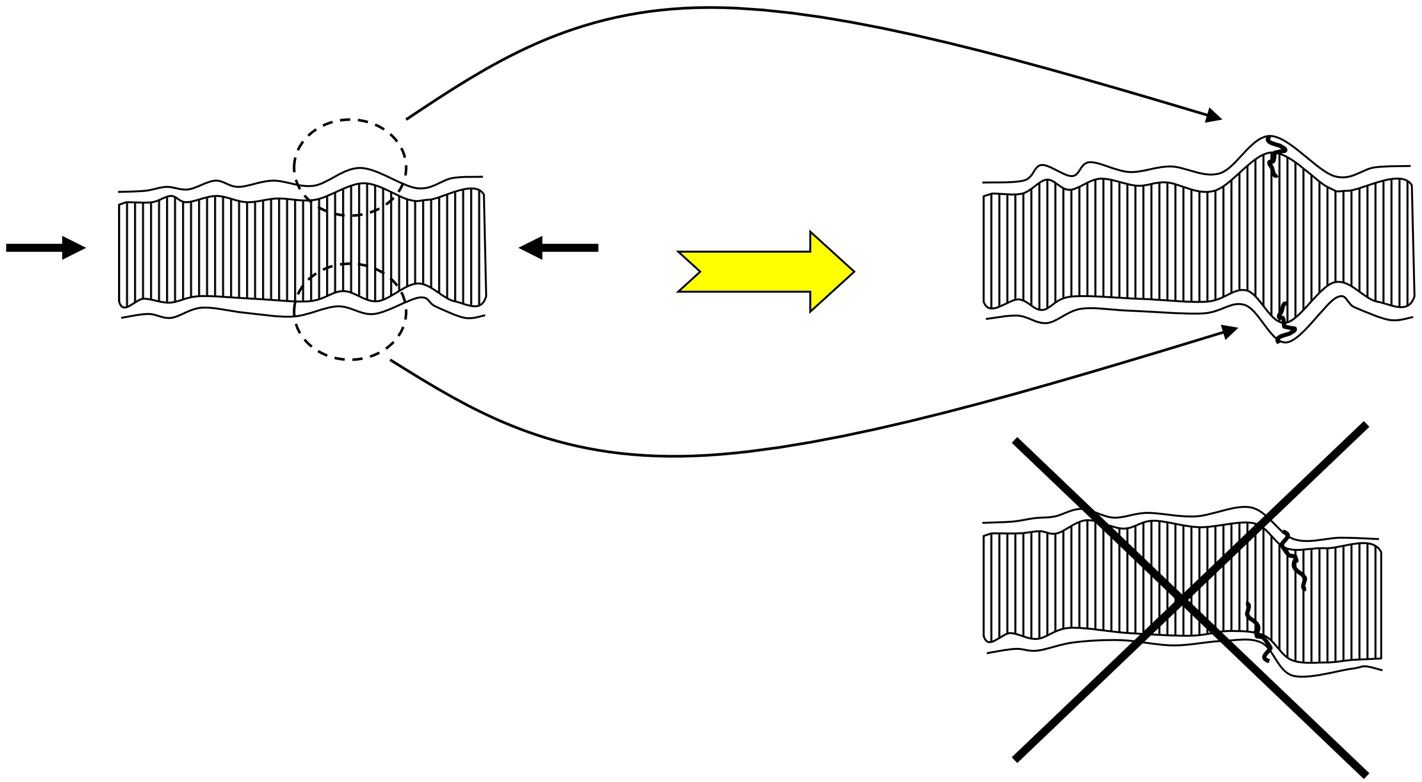
for 0.33 factor, see Sullins, R.T., Smith, G.W., Spier, D.D, “Manual for Structural Stability Analysis of Sandwich Plates and Shells”, NASA CR 1457, 1969, section 2

Implications of antisymmetric wrinkling equation



- as core thickness increases the wrinkling load decreases
- this is somewhat misleading; the equation is derived assuming perfectly flat facesheets; the waviness present changes things
- antisymmetric wrinkling occurs for very thin cores; for larger t_c values, the failure mode switches from antisymmetric to symmetric wrinkling
- it is common to use only the symmetric wrinkling equation in design and verify for shear crimping which is final outcome of antisymmetric wrinkling

Waviness favors symmetric wrinkling



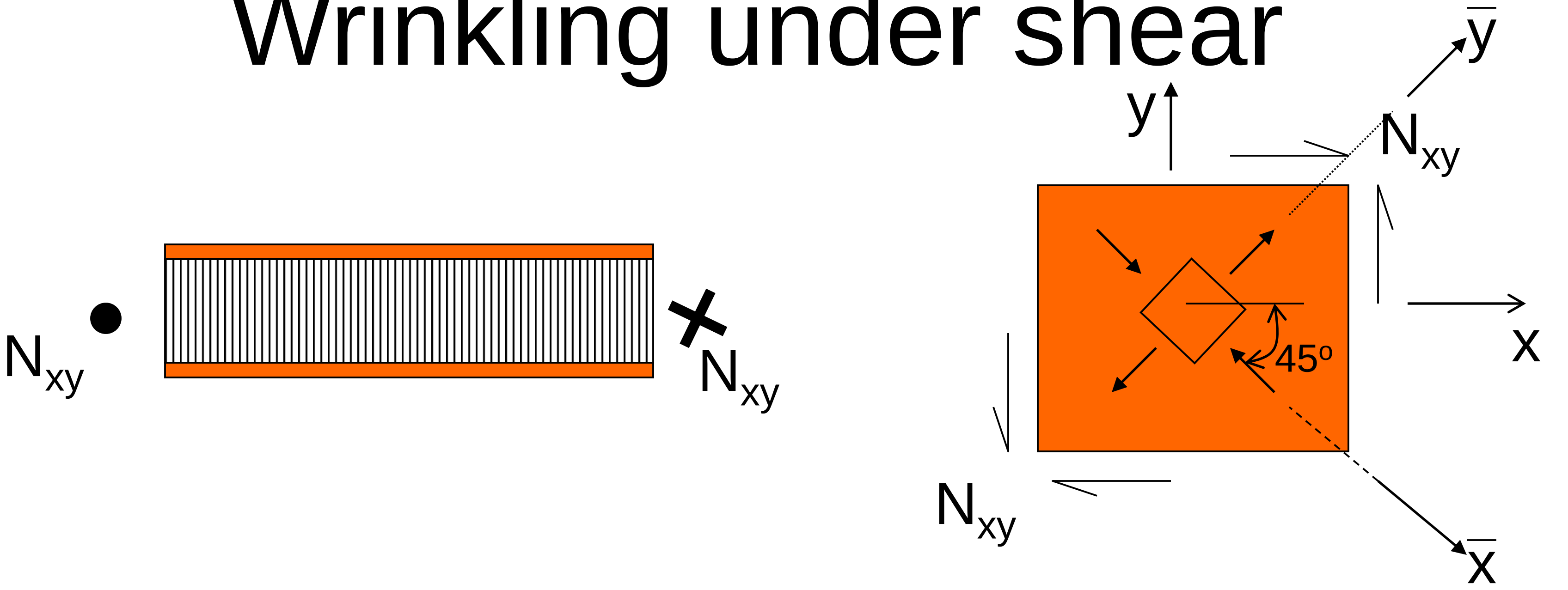
Correction to wrinkling equations

- for more accurate representation of composite facesheets, it is recommended to replace E_f in the previous equations:

$$E_f \rightarrow \frac{12(1-\nu_{xy}\nu_{yx})D_{11f}}{t_f^{\,3}}$$

- this assumes that the facesheet is wavy and its behavior is dominated by the bending modulus

Wrinkling under shear



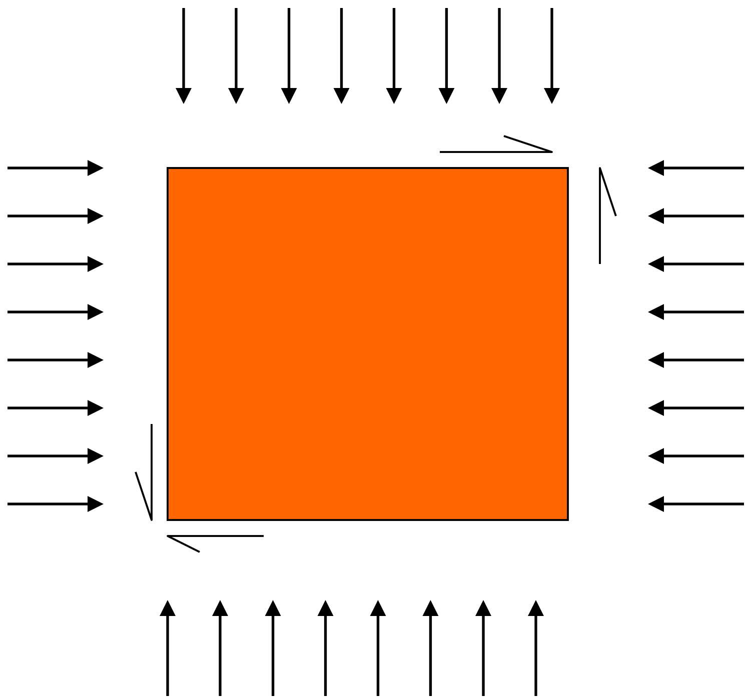
• since wrinkling is caused by the compressive load, calculate the wrinkling load at 45°

• this means the necessary quantities must be rotated 45 degrees:

$$G_{\bar{x}z} = \sin^2\theta G_{yz} + \cos^2\theta G_{xz} = \frac{G_{yz}+G_{xz}}{2} \quad for \quad \theta = -45^o$$

$$G_{\bar{y}z} = \cos^2\theta G_{yz} + \sin^2\theta G_{xz} = \frac{G_{yz}+G_{xz}}{2} \quad for \quad \theta = -45^o \qquad (5.5.3.2.20)$$

Wrinkling under combined loads(1)



- use interaction curves

(1) Birman, V., Bert, C.W., “Wrinkling of Composite Facing Sandwich Panels Under Biaxial Loading”, J Sandwich Structures and Materials, 6, 2004, pp. 217-237

Also: Ley, R.P., Lin, W., and Mbanefo, U., “Facesheet Wrinkling in Sandwich Structures”, NASA/CR-1999-208994, January 1999

Wrinkling under combined loads – Interaction curves

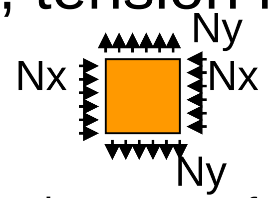
- biaxial compression

  x is the core “major” direction (with the higher shear stiffness and strength)

$$N_x = \frac{N_{xwr}}{\left(1+\left(\frac{N_y}{N_x}\right)^3\right)^{1/3}}$$

- compression in x direction, tension in y direction

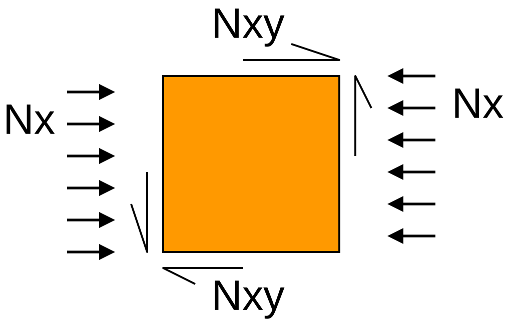
$$N_x = N_{xwr}$$



as before; tension neither helps nor deteriorates performance

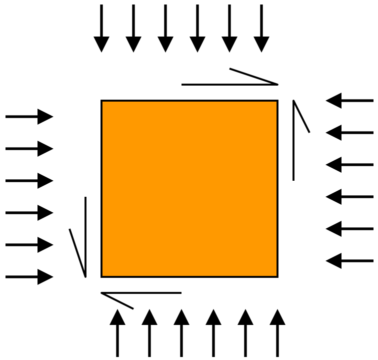
- compression and shear

$$R_c + R_s^2 = 1$$
$$R_c = N_x / N_{xwr}$$
$$R_s = N_{xy} / N_{xywr}$$



Wrinkling under combined loads – Interaction curves

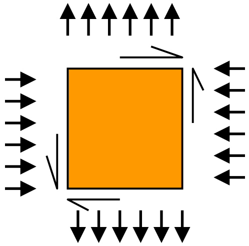
- biaxial compression and shear



$$R_c + R_s^2 = 1$$
$$R_c = N_x / N_{xwr}$$
$$R_s = N_{xy} / N_{xywr}$$

here N_{xwr} is wrinkling load in major core direction when biaxial loading acts alone!

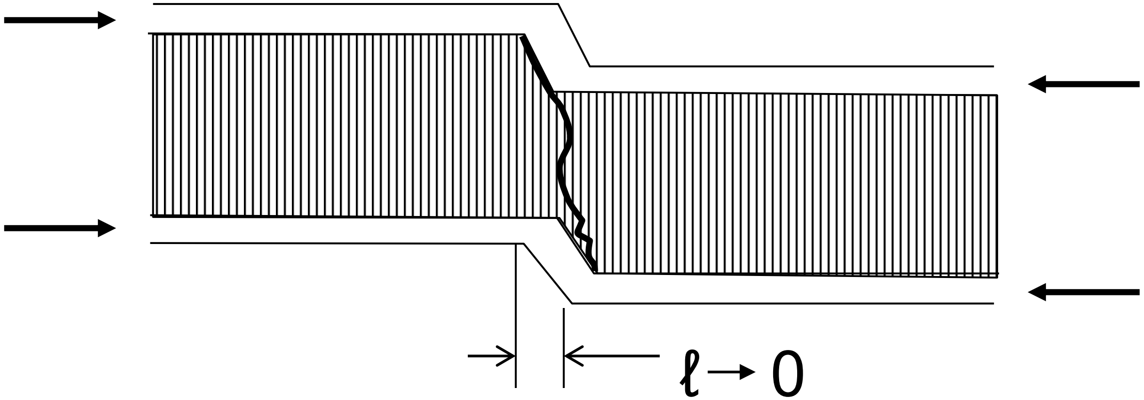
- compression in x dir, tension in y dir, and shear



$$R_c + R_s^2 = 1$$
$$R_c = N_x / N_{xwr}$$
$$R_s = N_{xy} / N_{xywr}$$

here N_{xwr} is wrinkling load in the compr. direction when compr. loading acts alone!

Shear crimping



• this is a failure mode that is very similar to the anti-symmetric wrinkling but with, essentially, zero wavelength

Shear crimping under compression

- if the wavelength tends to zero, the column buckling or local buckling N_{Ecrit} that depend on the wavelength go to infinity because

$$N_{Ecrit} \propto \frac{1}{\ell^2}$$

- using eq (5.5.3.1.2), which is the basic equation for sandwich buckling load, and setting $N_{Ecrit}=\infty$,

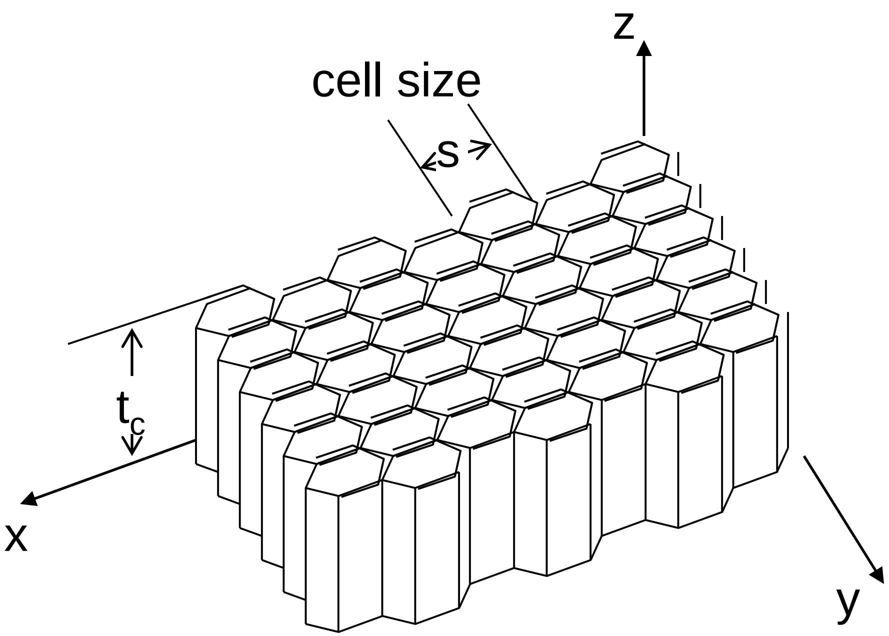
$$N_{crit} = \frac{t_c G_c}{\frac{t_c G_c}{N_{Ecrit}} + 1} \quad \xrightarrow{N_{Ecrit} \to \infty} \quad N_{crit} = t_c G_c \qquad (5.5.3.3.1)$$

with $G_c=G_{xz}$ or G_{yz} depending on the direction of loading

Shear crimping under shear

$$N_{xycrim} = t_c \sqrt{G_{xz} G_{yz}} \qquad (5.5.3.3.2)$$

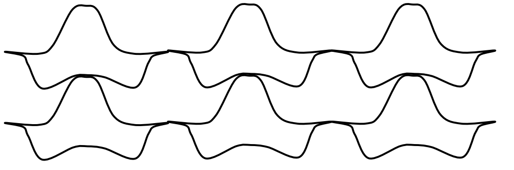
Dimpling or intracellular buckling



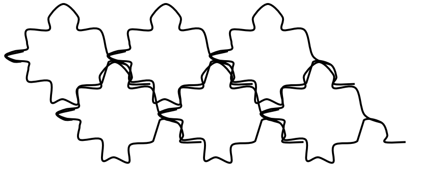
• for sufficiently large cell size s, the facesheet may buckle in between the cell walls=> dimpling

Dimpling or intracellular buckling

- a rigorous approach to determine the dimpling load would require determination of the buckling load for composite plates with non-rectangular shapes
  - hexagonal for regular Nomex, HFT, Korex, etc. cores
  - even more complex for flex-core



  - or double flex-core



Dimpling or intracellular buckling

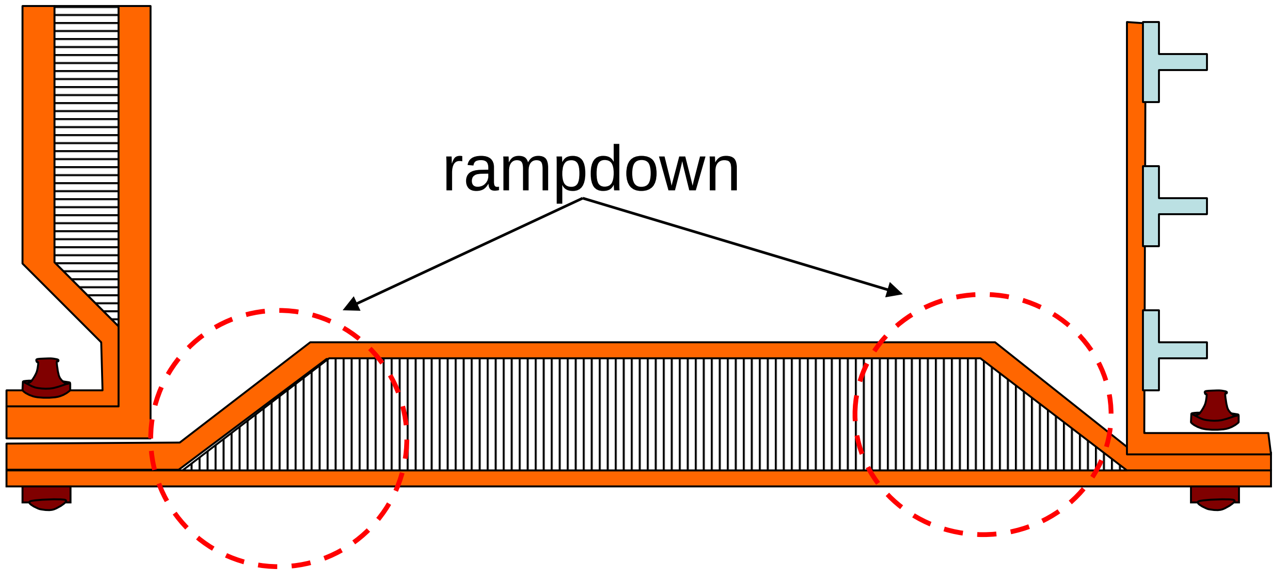
- instead, it can be shown by comparing to test results that the following expression, derived from column buckling considerations) is conservative:

$$N_{x\dim} = 2\frac{E_f t_f^3}{1-\nu_{xy}\nu_{yx}}\frac{1}{s^2} \qquad (5.5.3.4.1)$$

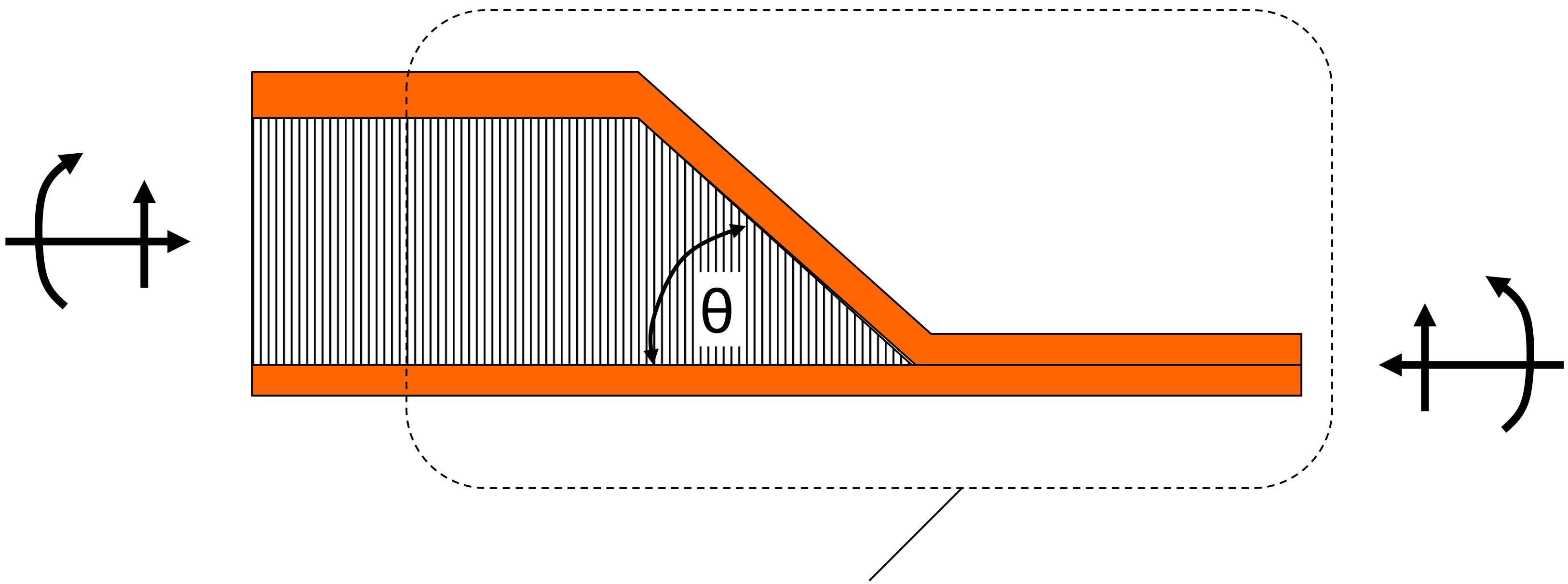
- with s the cell size obtained as the diameter of the circle shown below:

Other considerations for sandwich structure

- rampdown
  - – frequently, sandwich attaching to adjacent parts must be ramped down for better attachment and load transfer



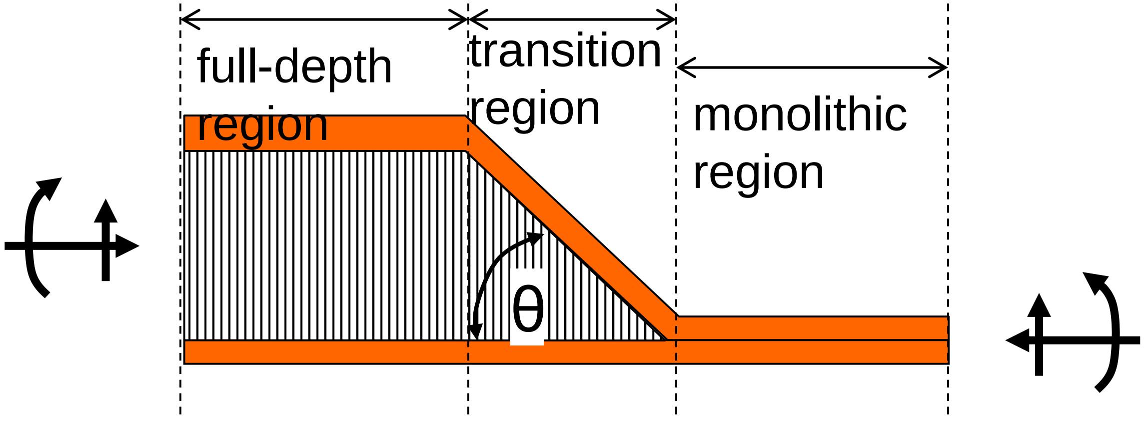
Rampdown considerations



Layup?

θ?

Rampdown considerations[1]



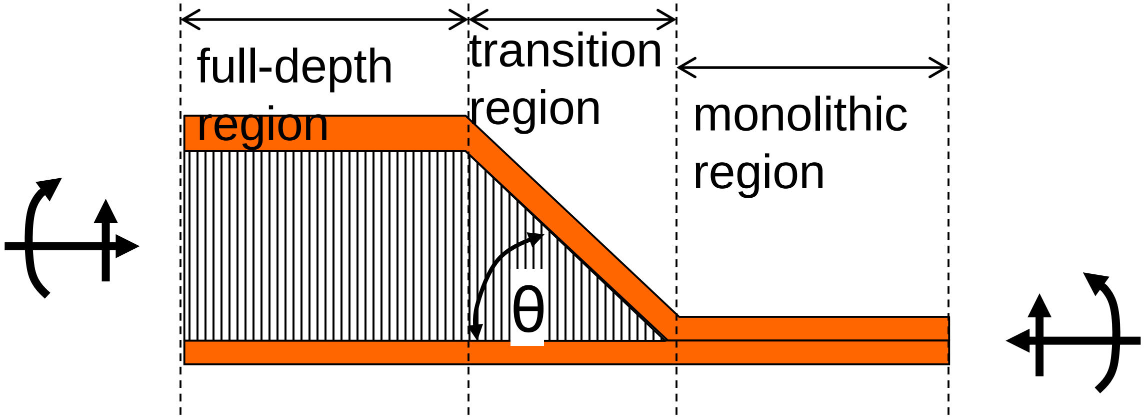
• eccentricity poses problems; sandwich bends even under in-plane load

• large deflections for typical panel size

1. Kassapoglou, C., "Stress Determination and Core Failure Analysis in Sandwich Rampdown Structures Under Bending Loads", Fracture of Composites, E. Armanios editor, TransTech Publications, Switzerland,

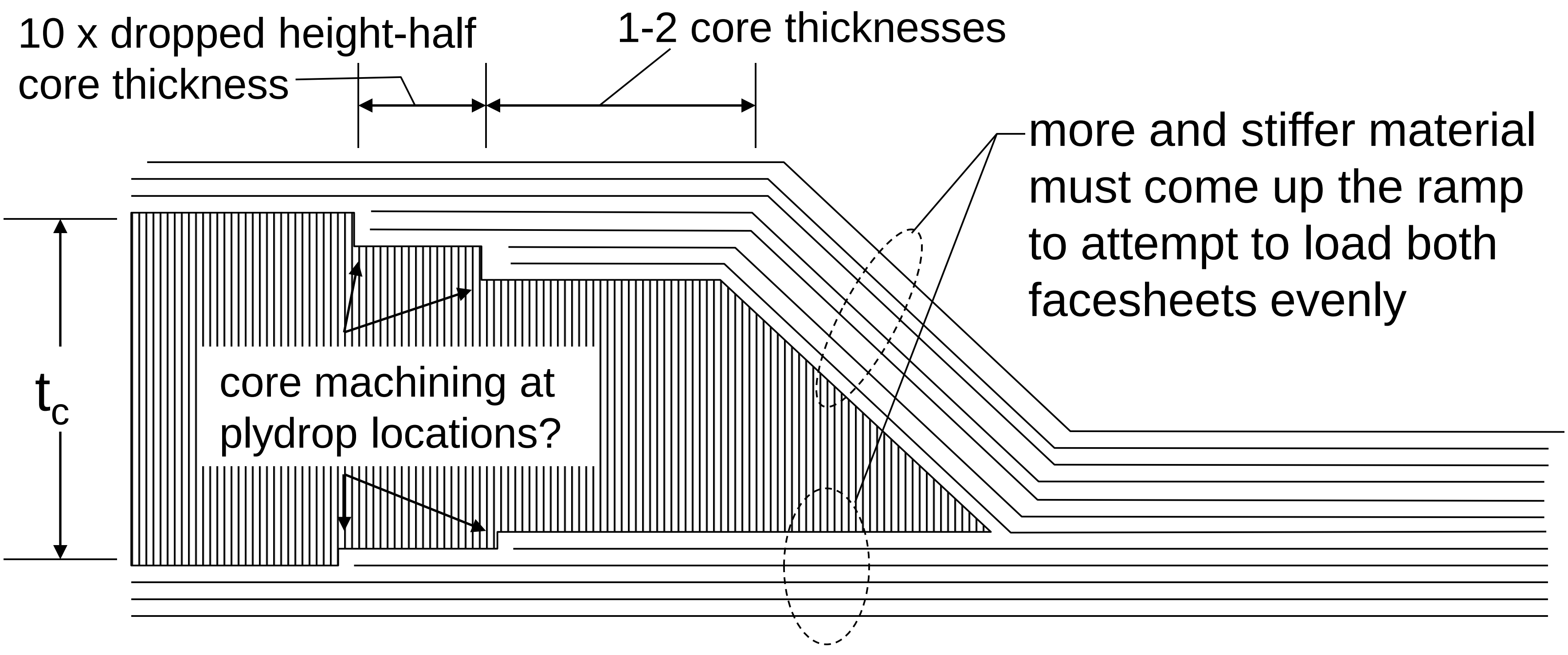
1996, pp 307-326

Rampdown considerations



- Layup:
  - – full-depth is determined by panel requirements (buckling, strength in the presence of damage, etc.)
  - – monolithic is determined by attachment requirements (bearing strength, bonded joint analysis, etc.)
  - – transition is a smooth transition from monolithic to full depth PROVIDED:

Rampdown considerations

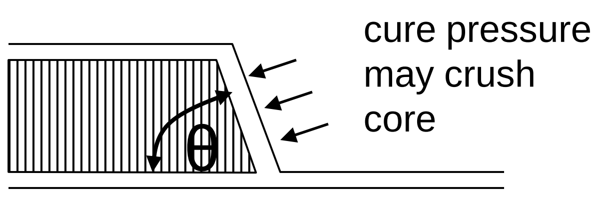


- sufficient plies go up the ramp to transfer load evenly

Rampdown considerations

- ramp angle θ

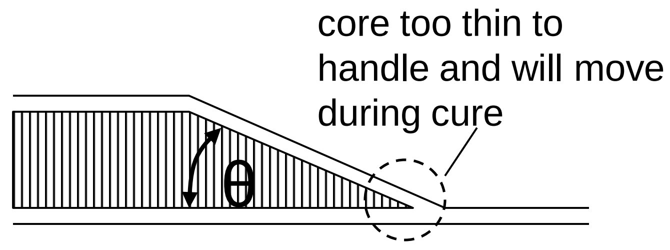
θ close to 90º



– very hard to get load up the ramp

– danger of crushing core from the edge during cure

θ close to 0º



– can achieve load distribution 60/40 among facesheets (or better)

– no crushing during cure (for θ≈40-45 need stabilization)

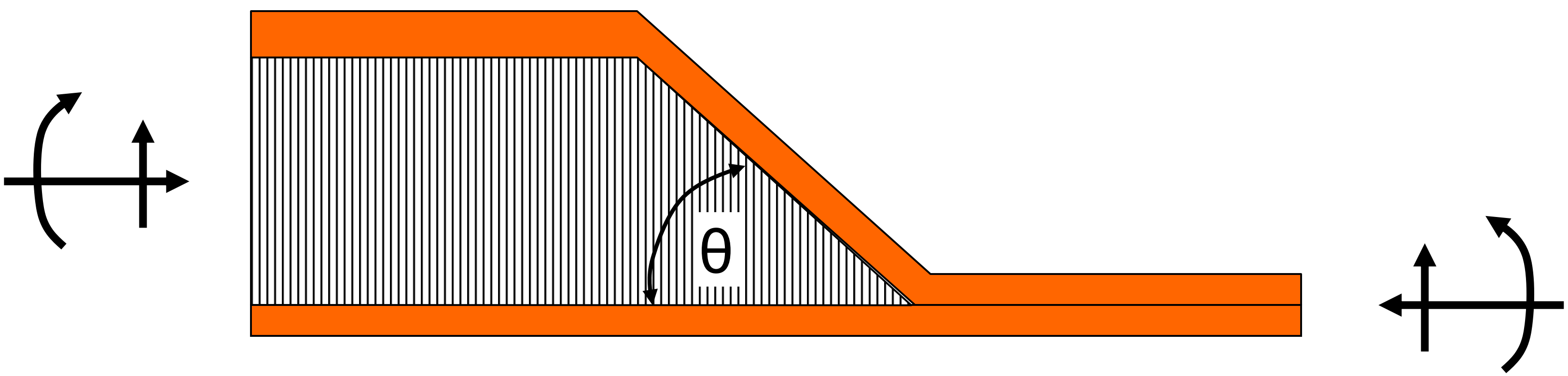
– large transition region => low bending stiffness

– handling and curing problems with core sharp edge

Rampdown considerations

• under certain assumptions[(1)] can show that the optimum angle is ~18 degrees

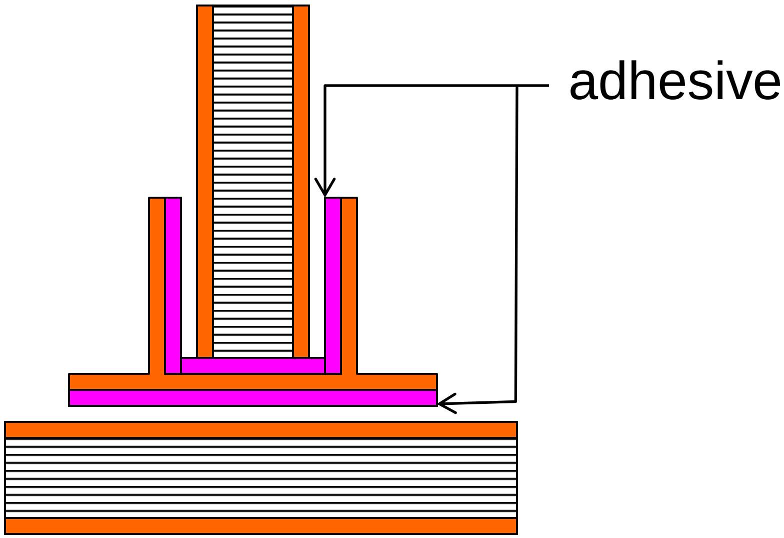
• in practice, angles 20-30 are preferred; 45 degrees to a lesser extent



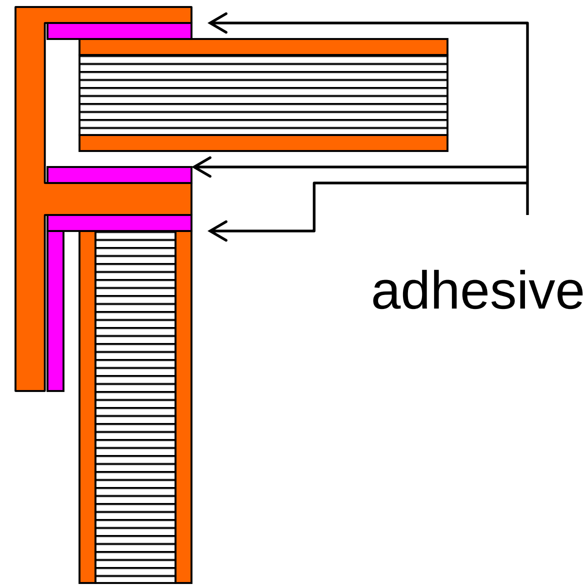
1. Kassapoglou, C., "Stress Determination and Core Failure Analysis in Sandwich Rampdown Structures Under Bending Loads", Fracture of Composites, E. Armanios editor, TransTech Publications, Switzerland,

1996, pp 307-326

Alternatives to rampdown



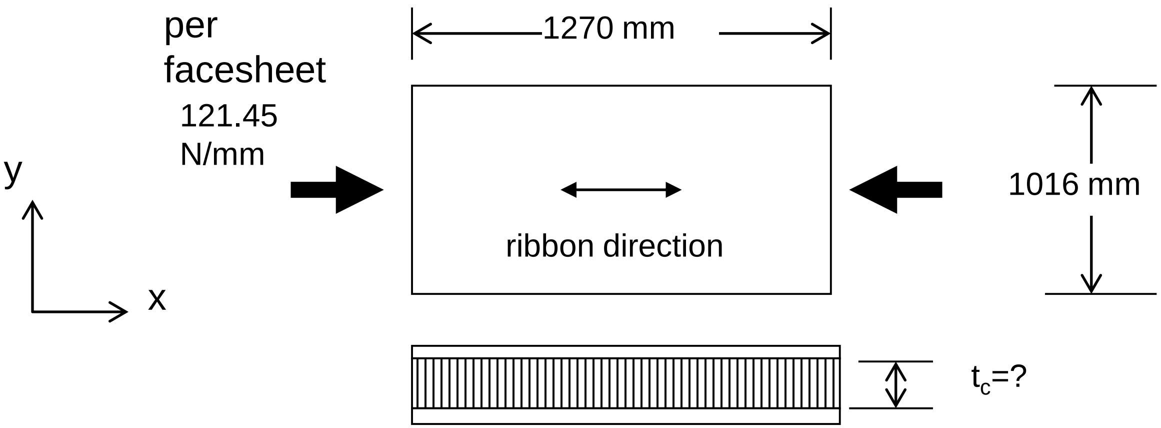
"Pi" joints



"F" joints

- if the joints are pre-cured, cannot use film adhesive; must use paste adhesive=> issues with bondline control
- can also co-cure (no adhesive?) if the facesheets are at least staged

Application 3 – Sandwich under compression



Basic mat'l properties:
Ex=137.88 GPa
Ey=11.03 GPa
Gxy=4.826 GPa
vxy=0.29
tply=0.1524 mm

Layup : [45/-45/0/core/0/-45/45]

Candidate core materials

	Material	E_c (MPa)	Gxz (MPa) (Ribbon direction)	Gyz (MPa)
core A	HRH-1/8-3.0	133.1	42.05	24.12
core B	HRH-3/16-3.0	122.7	39.29	24.12

cell size (units of inches)

density (units of lb/ft^3)

Application 3 – Sandwich under compression

1. Determine the minimum core thickness needed for each type of core material for the sandwich panel not to fail
2. What is the minimum core thickness needed if the core is misplaced and the ribbon direction rotated by 90 degrees? (sloppiness of manufacturing personnel)

Application 3 – Sandwich under compression

- from classical laminated-plate theory, for each facesheet

		45/-45/0	0/-45/45
	A11(N/mm)	34527.5	34527.5
	A12(N/mm)	10927	10927
	A16(N/mm)	0	0
	A22(N/mm)	15069.25	15069.25
	A26(N/mm)	0	0
	A66(N/mm)	11662	11662
	D11(Nmm)	713.1893	713.1893
	D12(Nmm)	153.7698	153.7698
	D16(Nmm)	112.9	112.9
	D22(Nmm)	223.7678	223.7678
	D26(Nmm)	112.9	112.9
	D66(Nmm)	166.5275	166.5275
Ef=	E1m(GPa)	1.02E+04	1.02E+04
	vxy	0.725	0.725
	vyx	0.317	0.317

← (D16, D26) not negligible any more; our results will be “approximate”

Application 3 – Sandwich failure modes

• from eq. (5.5.1) the bending stiffnesses for the entire sandwich are given by

$$D_{ij} = 2(D_{ij})_f + 2(A_{ij})_f \left(\frac{t_c + t_f}{2} \right)^2 \qquad (5.5.1)$$

• as the core thickness varies, the sandwich Dij terms are

tc (mm)-->	5.08	7.62	12.7	15.24	25.4	30.48	35.56	38.1
D11(Nmm)	530728.97	1127704	2989908	4255137	11543573	16524301	22396036	25666031
D12(Nmm)	167817.19	356743.1	946079.3	1346490	3653078	5229341	7087583	8122446
D16(Nmm)	225.8	225.8	225.8	225.8	225.8	225.8	225.8	225.8
D22(Nmm)	231457.4	492002.1	1304746	1856946	5037925	7211723	9774395	11201558
D26(Nmm)	225.8	225.8	225.8	225.8	225.8	225.8	225.8	225.8
D66(Nmm)	179110.17	380744.1	1009722	1437065	3898806	5581095	7564331	8668804

these are negligible again so panel buckling is not affected by disregarding them

Application 3 – Sandwich failure modes

- for panel buckling use eq (5.5.3.1.2)

$$N_{crit} = \frac{t_c G_c}{\frac{t_c G_c}{N_{Ecrit}} + 1} \qquad (5.5.3.1.2)$$

to substitute in eq. (5.5.3.1.3)

$$N_{Ecrit} = \frac{\pi^2 \left[D_{11} m^4 + 2(D_{12} + 2D_{66}) m^2 (AR)^2 + D_{22} (AR)^4 \right]}{a^2 m^2} \qquad (5.5.3.1.3)$$

	tc (mm)-->	5.08	7.62	12.7	15.24	25.4	30.48	35.56	38.1
	N_{Ecrit}(N/mm)	280.6621	596.4966	1581.712	2251.093	6107.102	8742.199	11848.69	13578.71
core A	N_{crit}(N/mm)	121.25851	208.3761	399.0801	498.6265	908.668	1117.284	1327.109	1432.343
Core B	N_{crit}(N/mm)	116.61081	199.2769	379.1845	472.797	857.4491	1052.843	1249.261	1347.741

lower than but almost equal to applied load

solution for buckling is between these two thicknesses

applied load = 121.45 N/mm

Application 3 – Sandwich failure modes

- for wrinkling, eq (5.5.3.2.18)

$$N_{xwr} = 0.43 t_f \left(E_f E_c G_{xz} \right)^{1/3} \qquad (5.5.3.2.18)$$

per facesheet!
x 2 for entire panel

	tc (mm)-->	5.08	7.62	12.7	15.24	25.4	30.48	35.56	38.1
core A	Nxwr(N/mm)	282.85831	282.8583	282.8583	282.8583	282.8583	282.8583	282.8583	282.8583
Core B	Nxwr(N/mm)	269.19049	269.1905	269.1905	269.1905	269.1905	269.1905	269.1905	269.1905

- wrinkling load is independent of the core thickness; both configurations (core A and core B) have wrinkling strength higher than the applied load => any core thickness will work

applied load = 121.45
N/mm

Application 3 – Sandwich failure modes

- the shear crimping load given by eq (5.5.3.3.1)

$$N_{crit} = t_c G_c$$ **for entire panel!** (5.5.3.3.1)

is always higher than the buckling load given by eq (5.5.3.1.2) so whichever core thickness works for buckling will also work for crimping

- for dimpling or intracellular buckling, the failure load, given by eq. (5.5.3.4.1)

$$N_{x\dim} = 2\frac{E_f t_f^3}{1-\nu_{xy}\nu_{yx}}\frac{1}{s^2}$$ **per facesheet!**

is independent of core thickness (x 2 for entire panel)

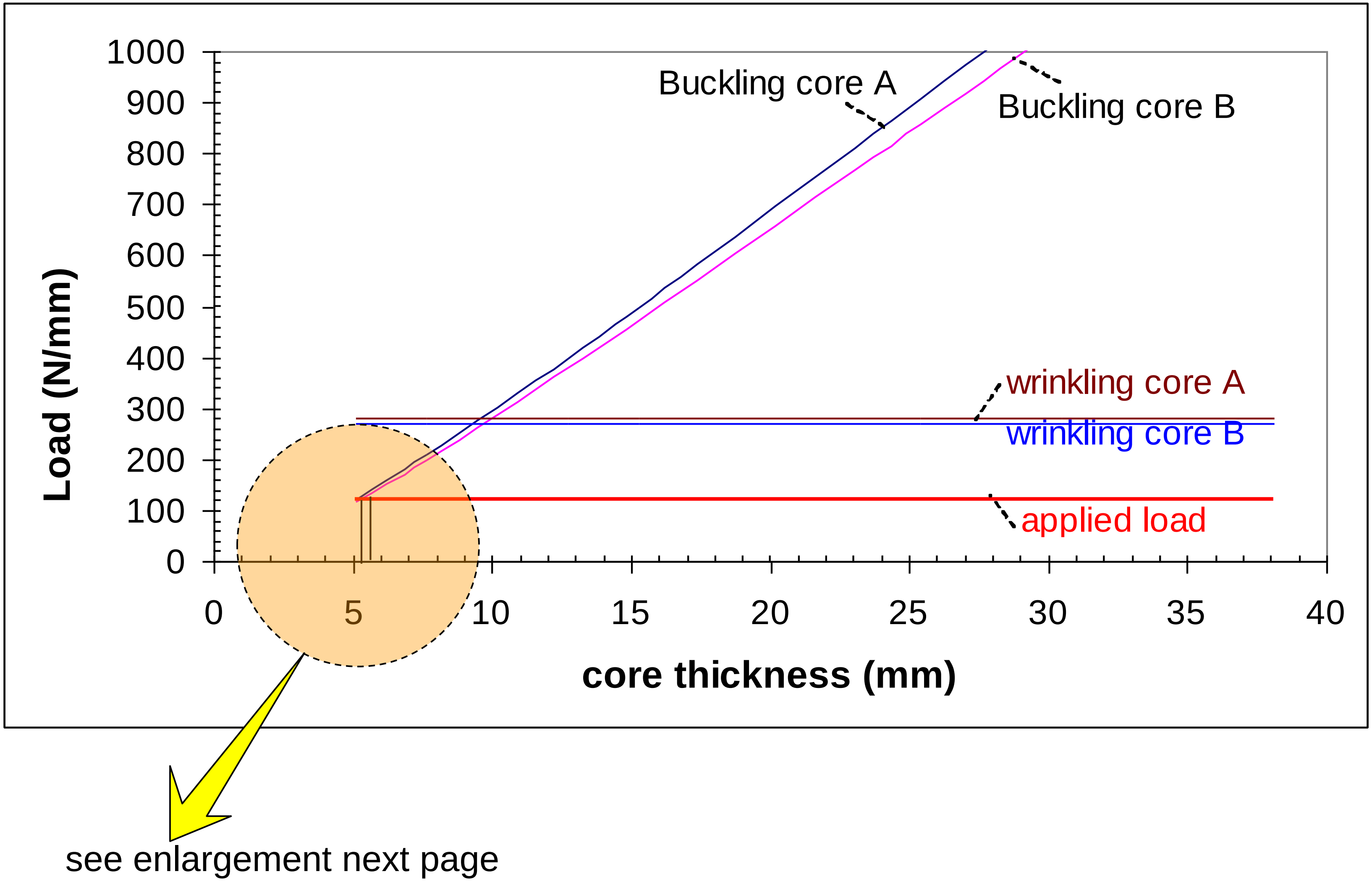
core A	Nxdim(N/mm)	3396.0192
Core B	Nxdim(N/mm)	1509.3419

same for all thicknesses

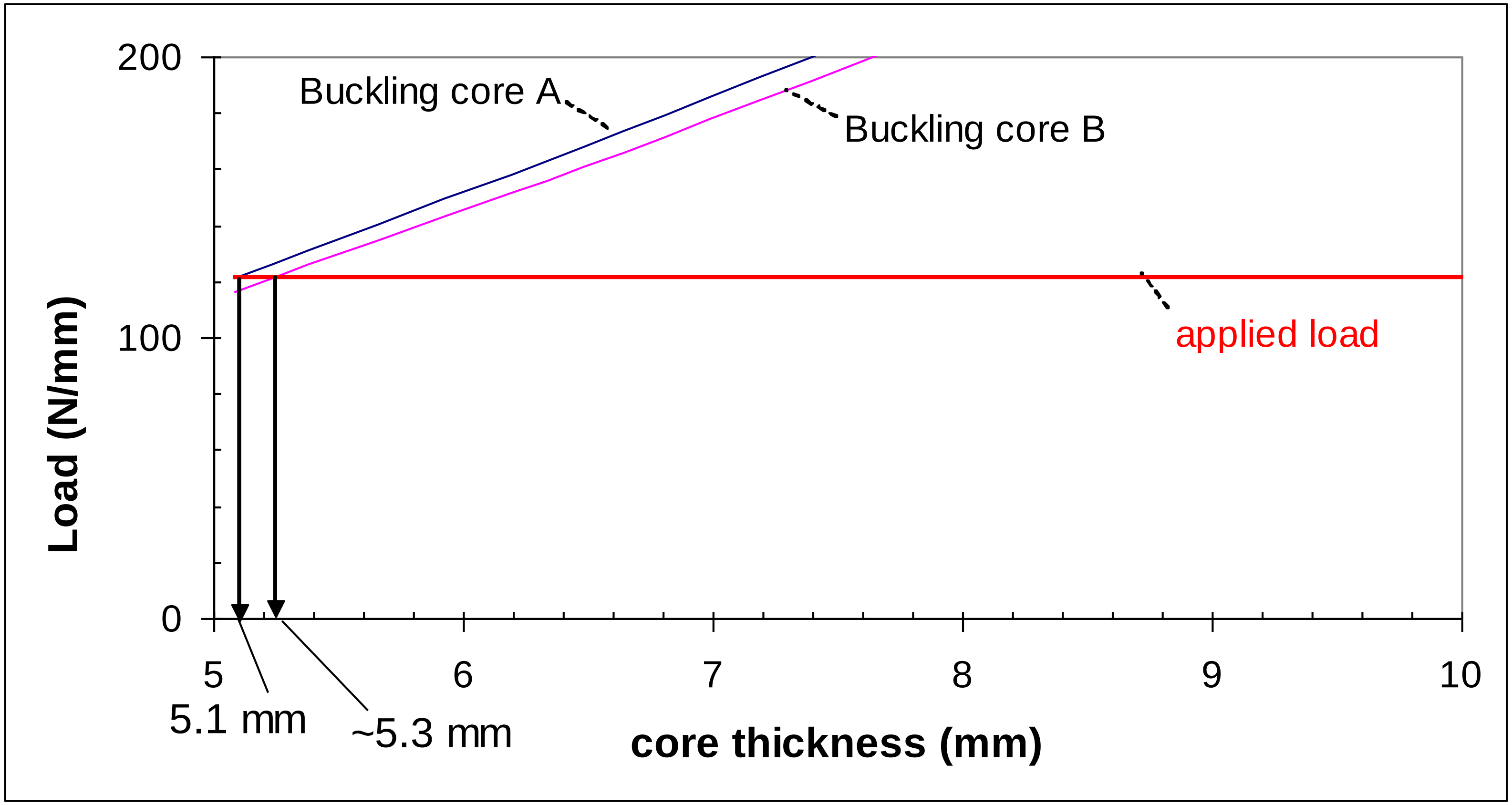
applied load = 121.45 N/mm

Application 3 – Sandwich failure modes

- summarizing all results,



Application 3 – Sandwich failure modes



- core thickness = 5.1 mm for core A and 5.3 mm for core B

Application 3 – Some thoughts

- strictly speaking, for such low core thicknesses, one should check if the core thickness selected satisfies the requirement implied by the wrinkling eq. used (that less than full core depth is effective in deformation); but because we are using the design eq with 0.43 factor instead of 0.91, there is (usually) no need to do that

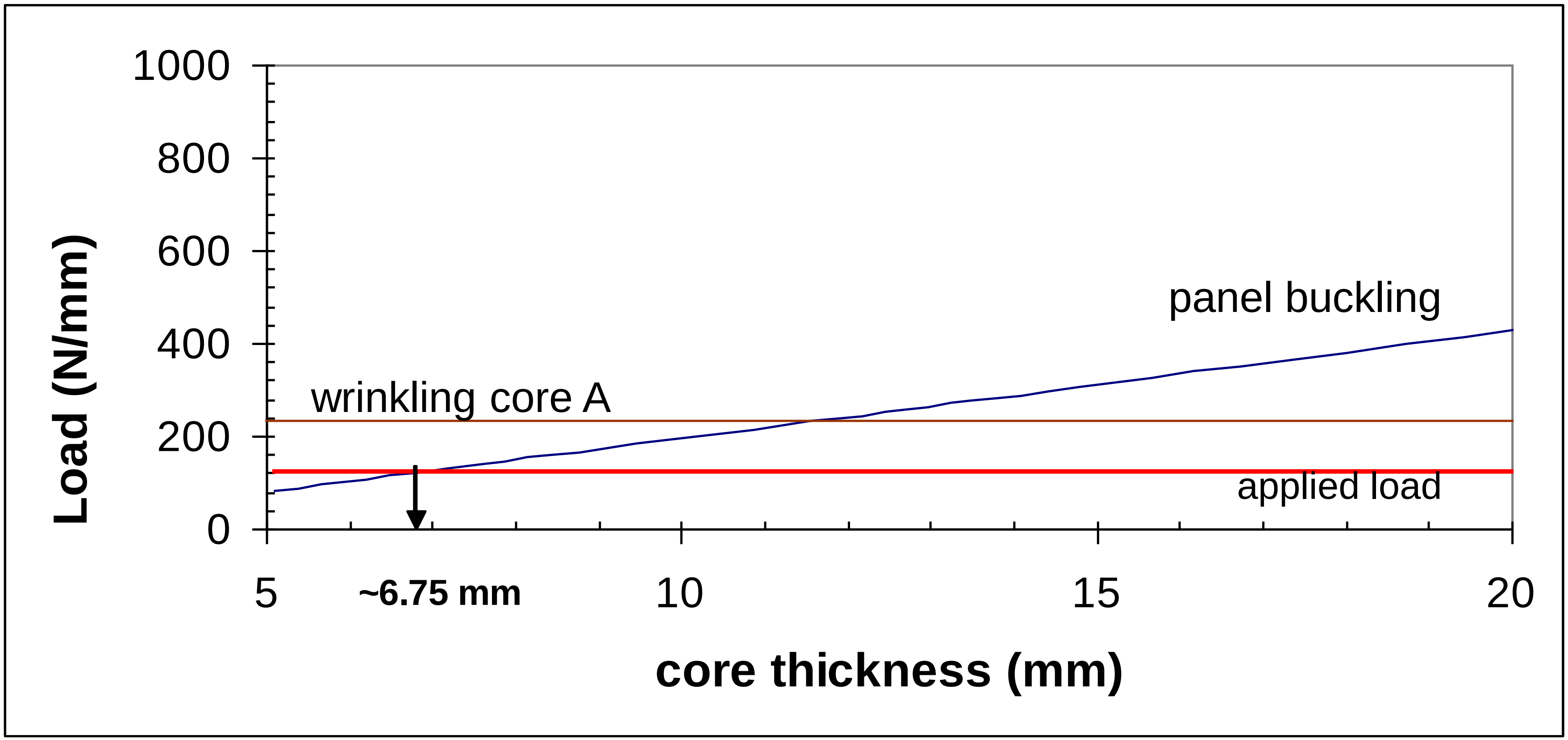
Application 3 – Part 2
(mislocating the core)

• in terms of core contribution to panel performance, the worst that can happen is to rotate the core by 90^o during manufacturing so the weakest direction is aligned with the applied load

• in this case the panel buckling and wrinkling loads are reduced significantly

•applying eqs. (5.5.3.1.2) and (5.5.3.2.18) but using Gyz instead of Gxz that was used before, gives the plot in the next page

Application 3 – Part 2
(mislocating the core)



applied load = 121.45 N/mm