Image Credit: Meyer Turku Oy

MARINE TECHNOLOGY GALA

Thickness optimization of insulating glass unit in cruise ships

Janne Heiskari

30.11.2022

Aalto University
School of Engineering

Prof. Jani Romanoff, Aalto University

D.Sc. Aleksi Laakso, Meyer Turku Oy

Prof. Jonas W. Ringsberg, Chalmers University of Technology

The 15th International Symposium on
PRACTICAL DESIGN OF SHIPS AND OTHER FLOATING STRUCTURES

Motivation and objective

- Cruise ships have many features to attract passengers
  - **Ship architecture → windows**
- Trend is to increase the **immersion** with the environment
  - Cabins, restaurants, lounges, domes etc.…
  - Glass domes can have $A > 2000\ m^2$ alone
  - The total area of windows reaches thousands of m^2
- Problem: ships have **lightweight requirement**
  - Density of glass $2500\ kg/m^3$ (more than concrete)
  - Large portion of windows located on the upper decks
  - Accumulated weight and decreased stability
- Solution:
  - Area and density fixed → reduce thickness → lightweight structure
- Objective of this presentation:
  - Ship windows
  - Current thickness determination
  - Is there room for improvement – if so, why?

https://sailorstaan.com/life-at-sea/oasis-of-the-seas/

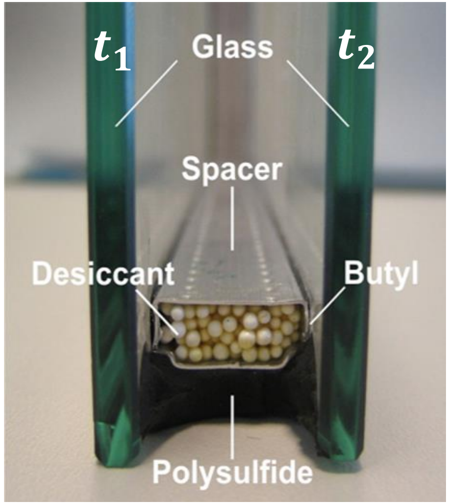
https://cruiselowdown.com/blog/2021/8/31/skydome-on-pando-iona

Introduction to insulating glass units

Mein Schiff 2, Meyer Turku Oy

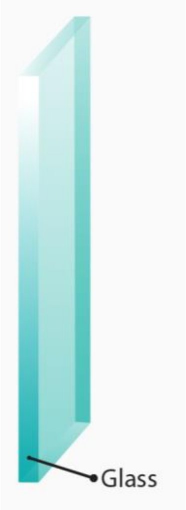
- Insulating glass unit (IGU) separate indoor and outdoor; thermal insulation due to the cavity (Figure)
  - The cavity is created by the two glass panes and the spacer
  - Glasses can be monolithic glasses or laminated glasses
- Present study: IGU consisting of **monolithic panes**
- Future study: IGU consisting of **laminated glasses** (omitted for now)

Insulating glass unit

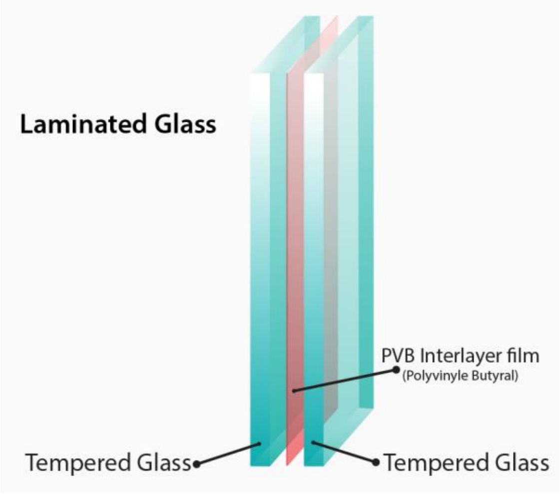


https://www.glastory.net/insulating-glass-types/

Monolithic glass



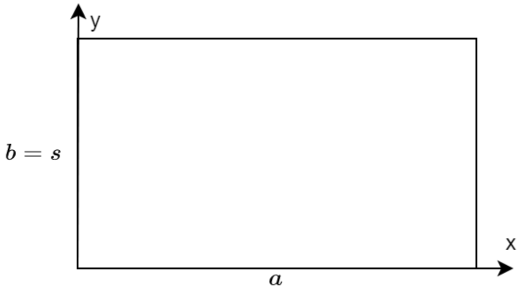
Laminated glass



https://www.fabglassandmirror.com/laminated

Thickness determination of the glass panes

- The Classification Societies provide easy-to-use equations
  - DNV, Lloyd's Register, and Bureau Veritas - practically identical
  - For example, **rectangular monolithic glass pane**: $t = 31.6s\sqrt{\frac{\beta p S_f}{R_m}}$ (Bureau Veritas, July 2022)



  - This equation is based on **linear** plate theory (strictly valid for $\boldsymbol{w < t/2}$)
  - For IGUs, the pane exposed to the load is calculated using the equation
  - There is no equation for the **unexposed pane**. Hence, we assume $t_1 = t_2$
- Is this feasible for modern cruise ships with large windows?

s: shorter side length
β: aspect ratio factor
p: design load
S_f: safety factor, 4
R_m: flexural strength (160 MPa for fully tempered glass)

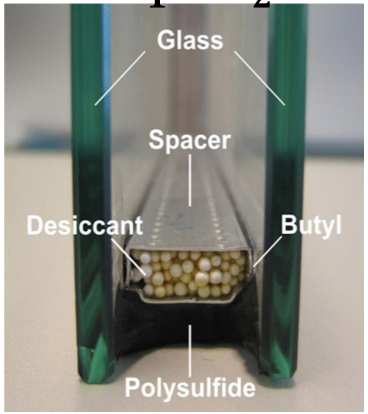
Example:
- 2.5 kPa design load
- $3m \times 2m\ (a \times b)$

$$t = 31.6 \times 2\sqrt{\frac{0.474 \times 4 \times 2.5}{160}}$$

$$t = 10.8\ \text{mm}$$

$$Max.principal\ stress\ 40\ MPa$$

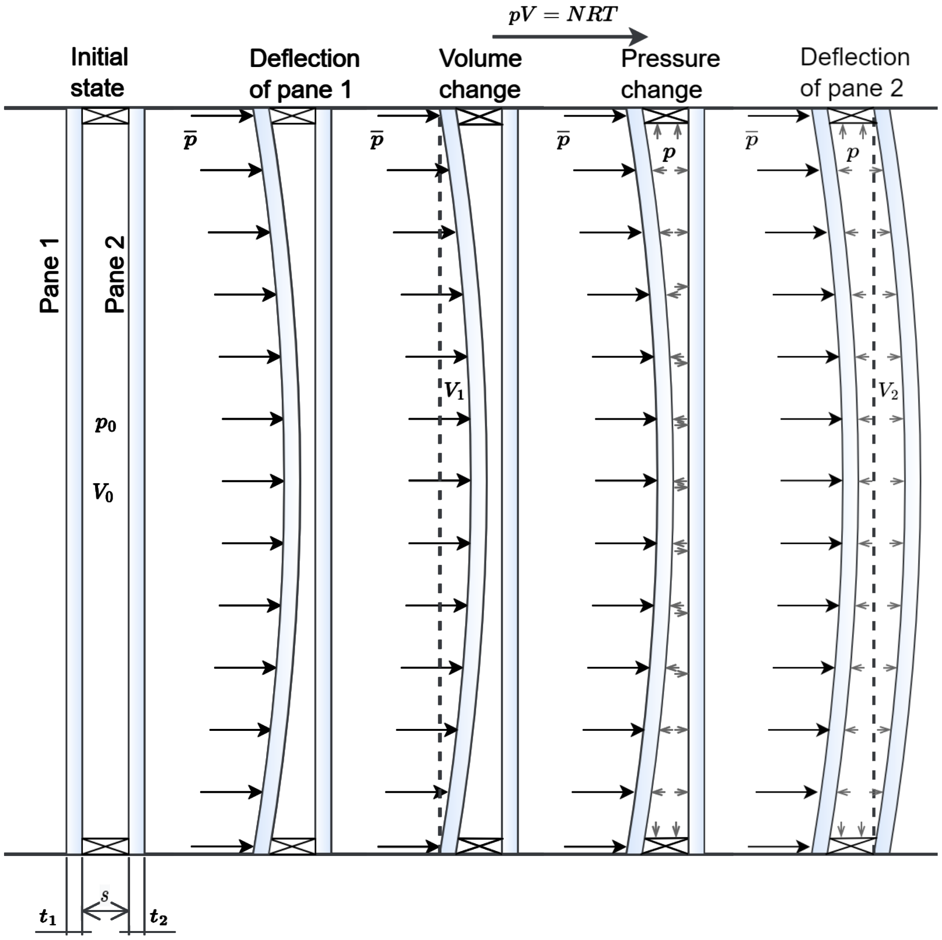
$$\boldsymbol{t_1 = t_2}$$



Load sharing

p = pressure, V = *volume*, N = *amount of substance*, R = *ideal gas constant*, T = *temperature*

- Structurally, the IGUs exhibit load sharing due to the sealed cavity
  - Analytical, numerical and experimental studies exists of load sharing
  - Implemented in building standards
- Faulty sealing → moisture → fog inside surface → repair
- Load sharing is significant for IGUs with compliant (large and thin) glass panes
  - Can be equal loading of the panes
  - Similar deflections and stresses
- The stresses are reduced
  - Maximum stress criterion → reduced thickness



Geometric nonlinearity

- Linear behavior
  - Relationship between applied load F and measured deflection w is linear (linear plate theory).
- Nonlinear behavior
  - **At large deflections**, this relationship does not hold
  - The midplane of the plate elongates → in-plane forces
  - The forces resist the deformation
  - Pronounced in thin-walled structures
  - **von Kármán strains (w/t)**

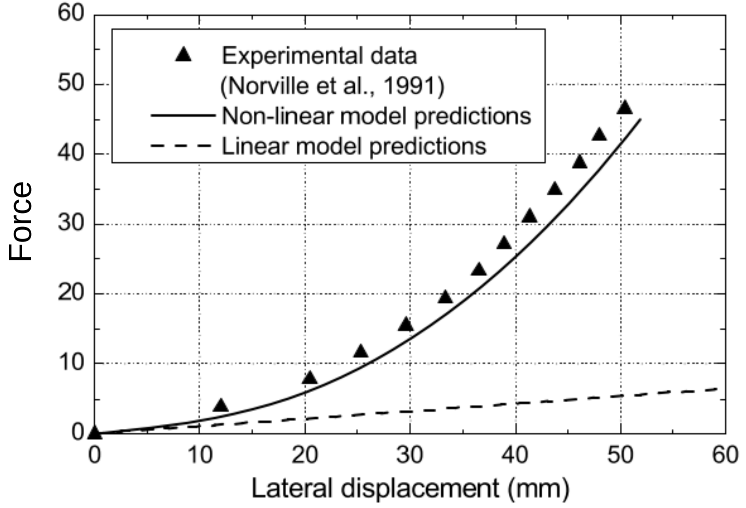
$$\varepsilon_{xx} = \frac{\partial u}{\partial x} + \frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2 - z\frac{\partial^2 w}{\partial x^2}$$

$$\varepsilon_{yy} = \frac{\partial v}{\partial y} + \frac{1}{2}\left(\frac{\partial w}{\partial y}\right)^2 - z\frac{\partial^2 w}{\partial y^2}$$

$$\varepsilon_{xy} = \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} + \frac{\partial w}{\partial x}\frac{\partial w}{\partial y} - 2z\frac{\partial^2 w}{\partial x \partial y}\right).$$

  - Reduced stress → reduced thickness

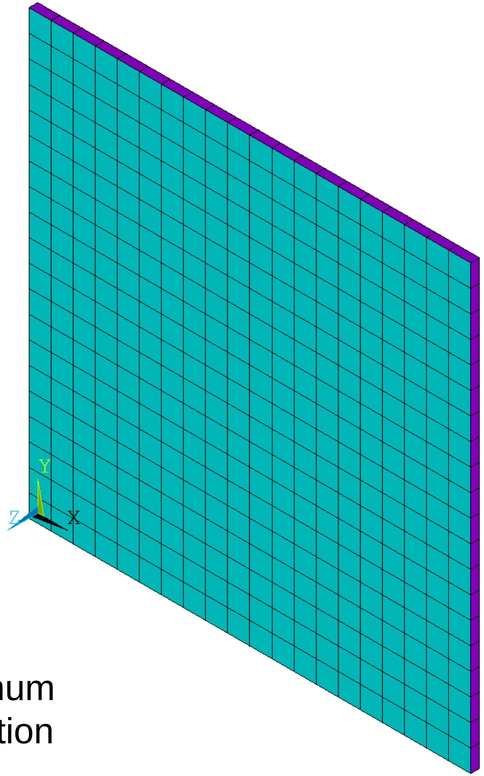
Load-deflection curve of fully tempered glass pane

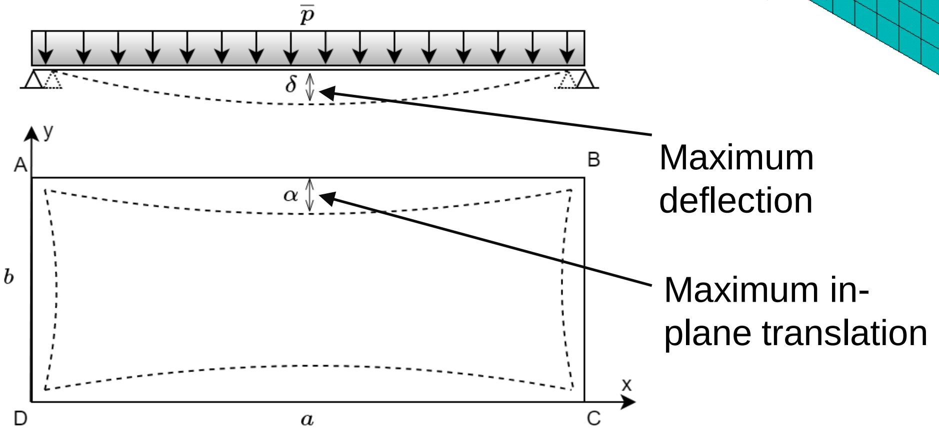


M. Haldimann, A. Luible and M. Overend, Structural Use of Glass, Zürich, Switzerland: IABSE-AIPC-IVBH, 2008

The IGU FE Model

- **Glass/spacers**:
  - 4-node structural SHELL181 elements (First order shear deformation theory)
- **Gas**:
  - 5-node hydrostatic fluid element (ideal gas law)
- **Boundary conditions:**
  - All 8 edges $UZ = 0$
  - Central nodes $UX = UY = 0$ (prevent rigid body motion)

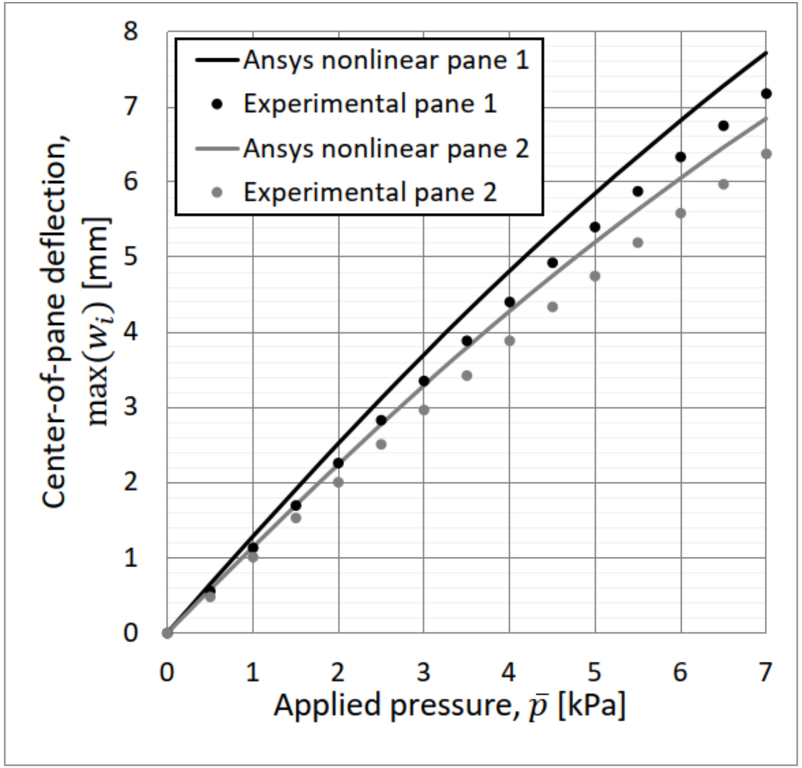




Aalto University
School of Engineering

The Model Validation

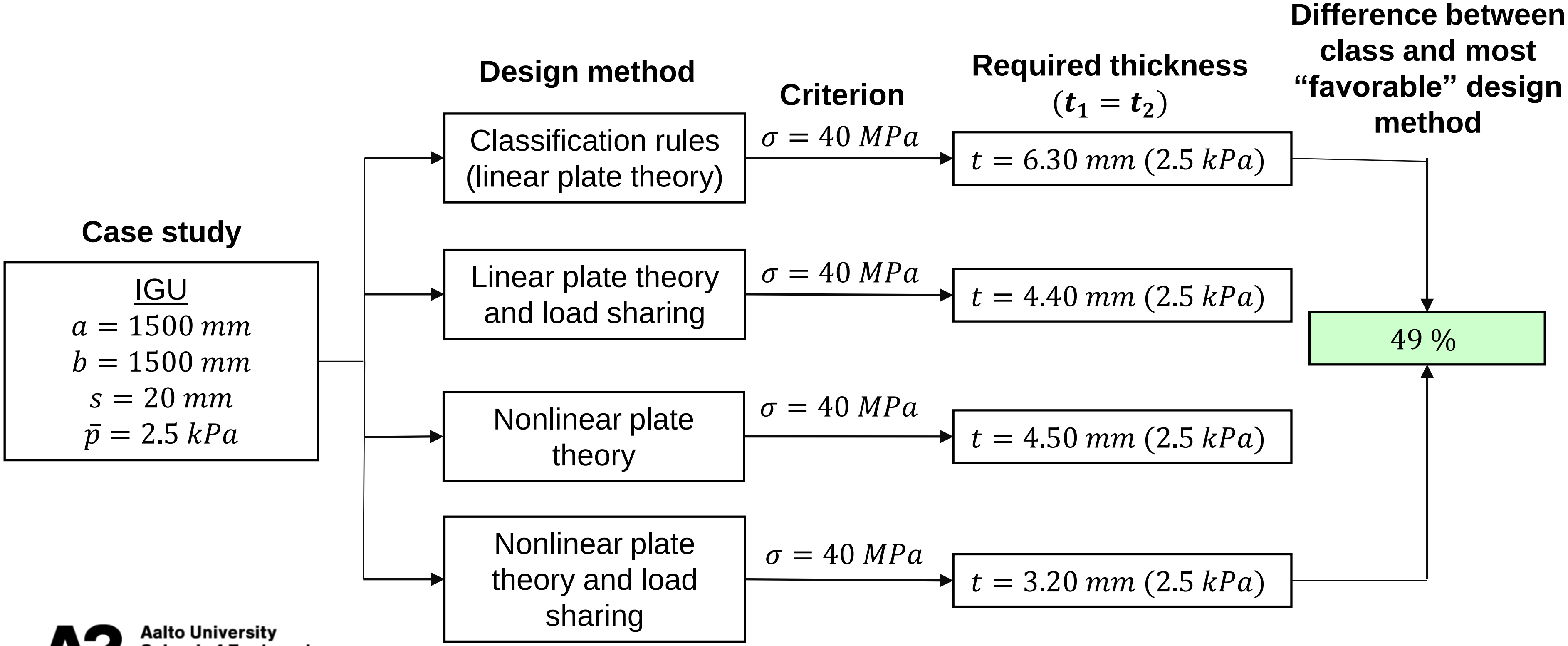
- Nonlinear Finite element results vs. experimental results by McMahon et al. (2018)
- Good agreement
- Slightly conservative



S. McMahon, H. Scott Norville, S.M. Morse, Experimental investigation of load sharing in insulating glass units, J. Archit. Eng. 24 (1) (2018) 04017038.

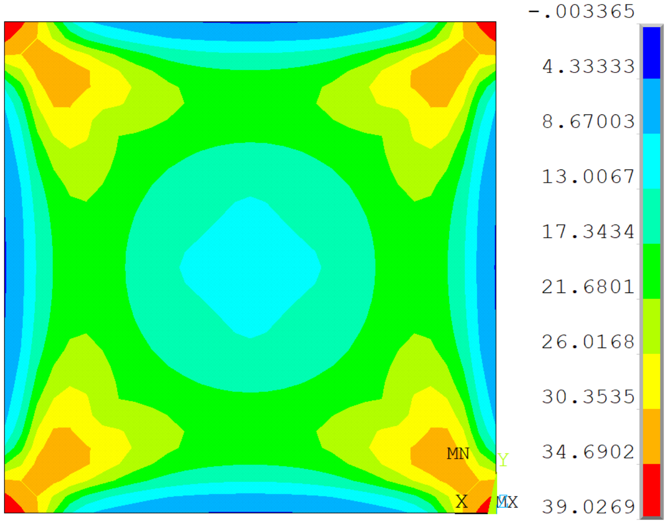
Implication of considering the effects

- **Results published in Journal paper**: On the thickness determination of **rectangular** glass panes in insulating glass units considering the <u>load sharing</u> and <u>geometrically nonlinear</u> bending.



Response of the optimized thickness

Maximum principal stress of exposed pane



Response

$\sigma_1 = 39\ MPa$
$\sigma_2 = 38\ MPa$
$w_1 = 22\ mm$
$w_2 = 21.5\ mm$
$LS = 49\ \%$

<u>IGU</u>

$a = 1500\ mm$
$b = 1500\ mm$
$s = 20\ mm$
$\bar{p} = 2.5\ kPa$

Nonlinear plate theory and load sharing

$\sigma = 40\ MPa$

$\boldsymbol{t = 3.20\ mm}\ (2.5\ kPa)$

Aalto University
School of Engineering

Large deflections

https://www.morglass.com/factors-that-caused-glass-curtain-wall-visual-distortion.html

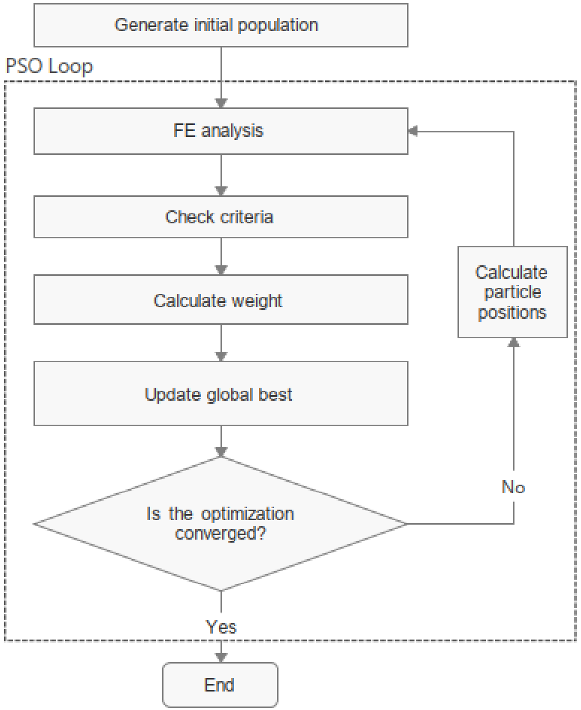
- Presented method + stress criterion → **large deflections**
  - Visual distortion
  - Potential feeling of unsafe
  - Harm integrity of the sealing systems
- Introduce deflection limit b/k
  - What should k be?
  - No class rules
- We choose $k = 175$ and $k = 100$
- Find minimum thickness under multiple design constraints → Particle Swarm Optimization (PSO)
- Question: how sensitive are the thickness to the deflection limit?

https://www.cruisecritic.com/photos/ships/celebrity-equinox-382/sky-observation-lounge-203522/sky-observation-lounge--v10422251/

Aalto University
School of Engineering

Case study

- Square IGU $a/b = 1$
  - $b = 2000/3000/4000/5000$
- Rectangular IGU $a/b = 3$
  - $a = 2100/3000/4200/5100$ (longer side)
  - $b = 700/1000/1400/1700$ (shorter side)
- Design load 2.5 kPa
- Design constraints
  - Maximum deflection – ∞ & $b/100$ & $b/175$ (3 cases)
  - Maximum principal stress – 40 MPa
  - Maximum in-plane translation – 2 mm
- Weight: $a \times b \times t \times 2 \times 2500$
- Repeat PSO until optimum thickness is found



Results - the optimized thickness with different criteria

- Without deflection limit

Size ($a \times b$) [mm]	$t_{class}[mm]$	$t_{FEM}[mm]$	Saving [%]	Size ($a \times b$)	$t_{class}[mm]$	$t_{FEM}[mm]$	Saving [%]
2000×2000	8.4	4.2	50	2100×700	4.7	2.2	52
3000×3000	12.6	6.2	51	3000×1000	6.7	3.2	52
4000×4000	16.8	8.2	51	4200×1400	9.3	4.4	53
5000×5000	21.0	10.3	51	5100×1700	11.4	5.3	53

→ 50 % to 53 % thinner than class rules suggest

- With $b/100$ deflection limit

Size ($a \times b$) [mm]	$t_{class}[mm]$	$t_{FEM}[mm]$	Saving [%]	Size ($a \times b$)	$t_{class}[mm]$	$t_{FEM}[mm]$	Saving [%]
2000×2000	8.4	6.5	22	2100×700	4.7	4.4	6
3000×3000	12.6	9.7	23	3000×1000	6.7	6.3	6
4000×4000	16.8	13.0	23	4200×1400	9.3	8.8	6
5000×5000	21.0	16.2	23	5100×1700	11.4	10.6	6

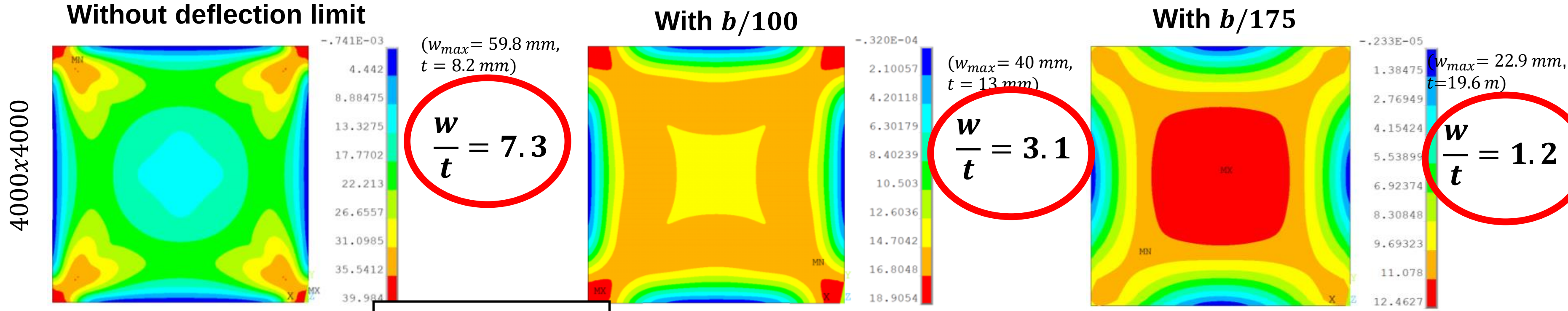
→ 6 % to 23 % thinner

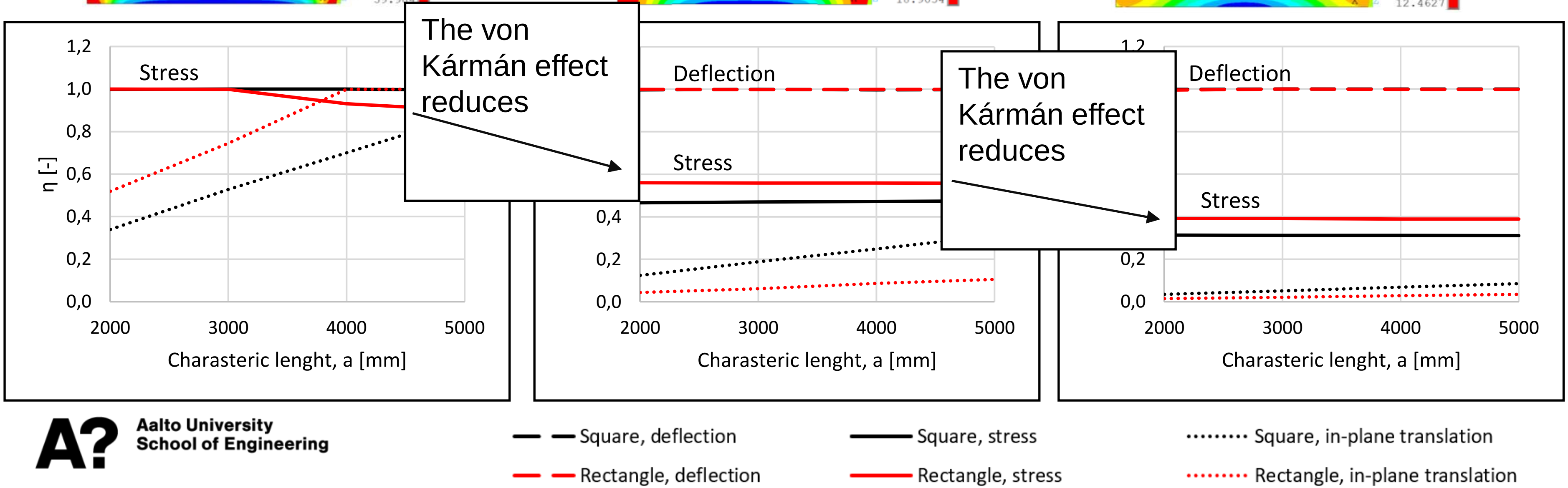
- With $b/175$ deflection limit

Size ($a \times b$) [mm]	$t_{class}[mm]$	$t_{FEM}[mm]$	Saving [%]	Size ($a \times b$)	$t_{class}[mm]$	$t_{FEM}[mm]$	Saving [%]
2000×2000	8.4	9.8	-17	2100×700	4.7	5.4	-16
3000×3000	12.6	14.7	-17	3000×1000	6.7	7.7	-15
4000×4000	16.8	19.6	-17	4200×1400	9.3	10.7	-14
5000×5000	21.0	24.4	-16	5100×1700	11.4	13.0	-14

→ -14 % to -17 % (class rules provide thinner solution)

Results - activation of the criteria - $\eta = response/criterion$





Aalto University
School of Engineering

Conclusion and future work

- Conclusions:
  - Increased usage of IGUs require more advanced design methods
  - Stress criterion may not be sufficient
  - The thickness results are sensitive to the chosen deflection limit
  - Thickness savings of 6 % to 23 % ($b/100$) still desirable considering total area of IGUs in ships
- Future work:
  - Release assumptions (under journal review)
    - Expand optimization to other shapes (circular, triangular)
    - Use unequal thicknesses
  - Perform experimental work on IGUs consisting of **laminated glasses**
    - Influence of large deflection on IGU behavior
    - Further validate FE model

Collaborations

- Meyer Turku Oy – Finland
- Chalmers University of Technology – Sweden, Gothenburg

Thank you

Appendix: Particle Swarm Optimization (PSO)

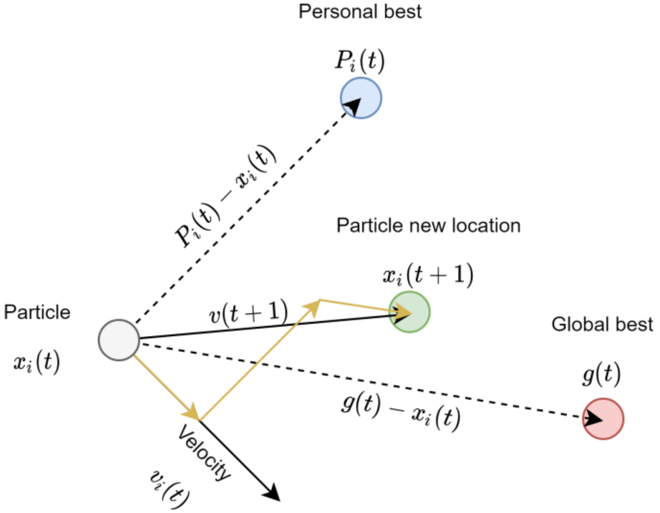
- PSO introduced in 1995 [1] for nonlinear optimization problems.
- Metaheuristic algorithm based on social behavior of animals
- Trial and error of the objective function (no gradient)
- Suitable for variety of engineering problems
- Easy to implement
- At each new iteration, a new position for the particle is calculated:

$$\vec{x}_i(t+1) = \vec{x}_i(t) + \vec{v}_i(t+1) \quad (E1)$$

- The new velocity vector is calculated:

$$\vec{v}_i(t+1) = w\vec{v}_i(t) + r_1 c_1 \left(\vec{P}_i(t) - \vec{x}_i(t)\right) + r_2 c_2 \left(g(t) - \vec{x}_i(t)\right) \qquad (E2)$$

https://figmentums.com/2016/09/12/swarm-stupidity-in-humans/



Aalto University
School of Engineering

[1] Kennedy J., Eberhart R., (1995) Particle Swarm Optimization

The IGU FE Model

- **Glass/spacers**:
  - 4-node structural SHELL181 elements (First order shear deformation theory)
- **Gas**:
  - 5-node hydrostatic fluid element (ideal gas law)
- **Boundary conditions:**
  - All 8 edges $UZ = 0$
  - Central nodes $UX = UY = 0$ (prevent rigid body motion)