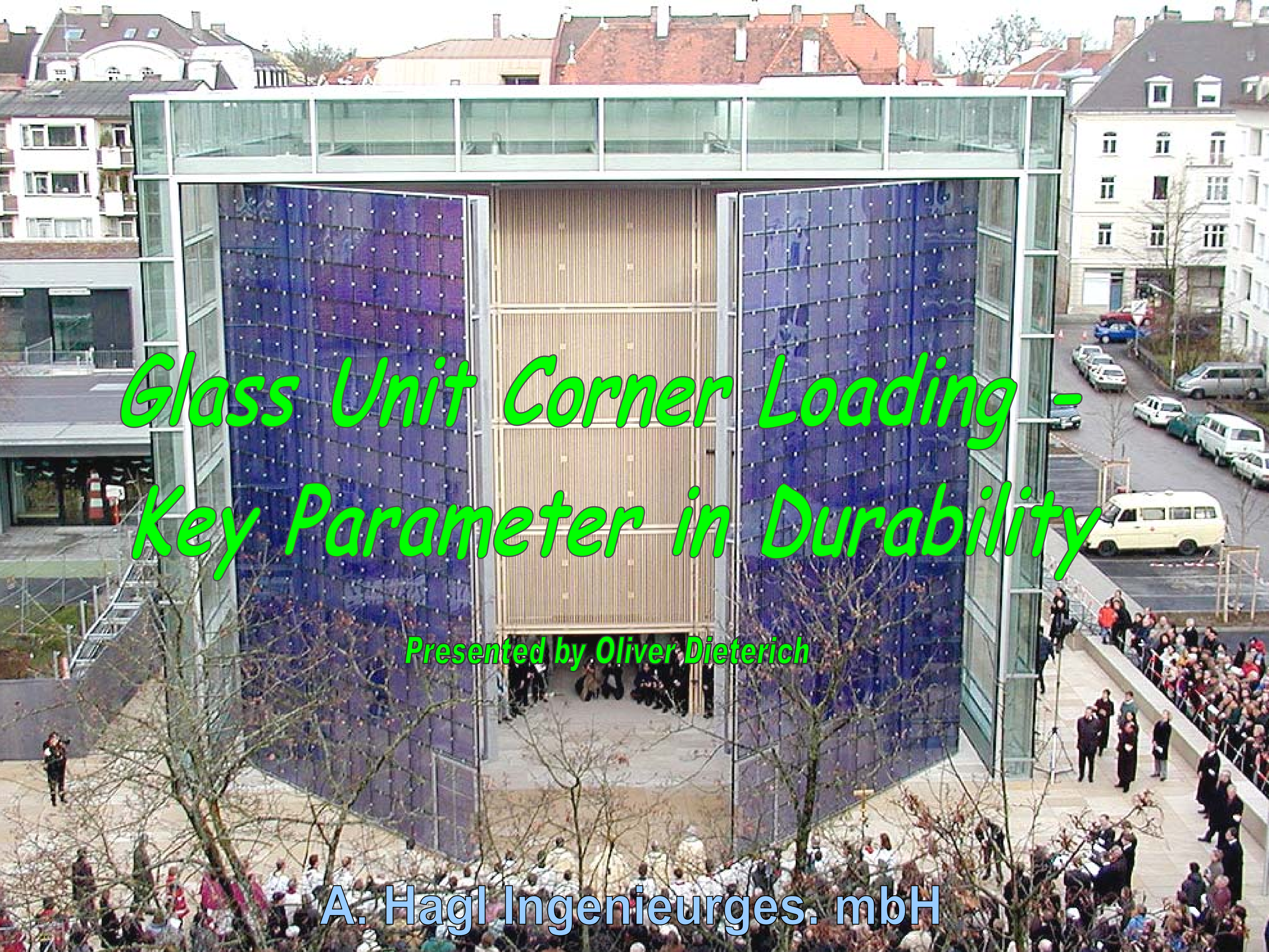
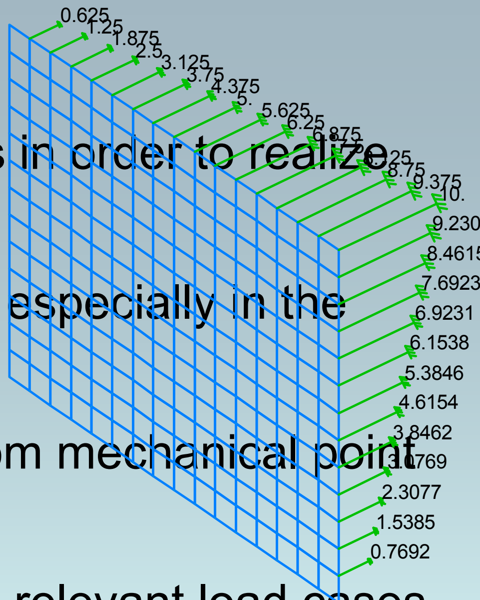
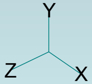

Glass Unit Corner Loading -
Key Parameter in Durability
Presented by Oliver Dieterich
A. Hagl Ingenieurges. mbH

Motivation





- Increasing interest from architecture for cold bent glass units in order to realize curved glass façades
- Warping of glass units leads to permanent adhesive loading especially in the unit corner areas.
- Interaction with wind or snow loads might affect durability from mechanical point of view.
- Thus, a detailled knowledge of adhesive corner loads due to relevant load cases is of interest.
- The European Technical Guideline ETAG 002 does not adequately consider wind corner loads.

- Note: Results presented during 4th International Symposium on the Application of Architectural Glass, organised by Prof. Siebert, University of Armed Forces München, October 4 and 5 2010.

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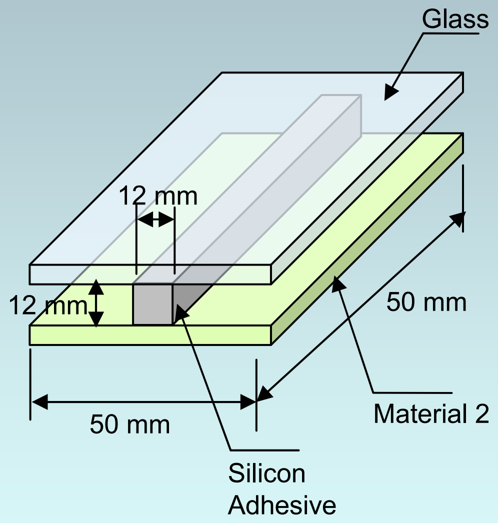
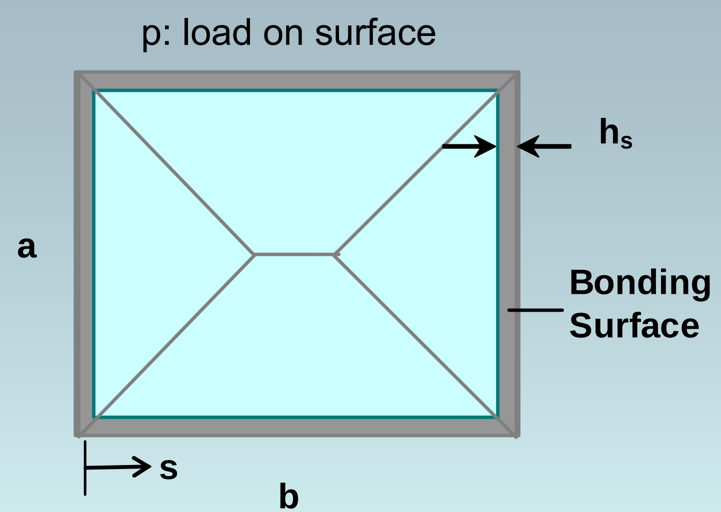
Bonding Design According ETAG 002

- Line-type bonding designs for structural glazing systems are covered by European guideline ETAG 002.
- ETAG 002 is limited to simple geometries - rectangular cross section and a two-sided joint design.
- For material approval a special H-type specimen is defined in ETAG 002 for determination of mechanical limits.
- <u>Please note:</u> The operating conditions of ETAG 002 do not require much knowledge of the adhesive material properties.



Design Rules According ETAG 002



The stress in the middle of the longer edge is calculated as follows:

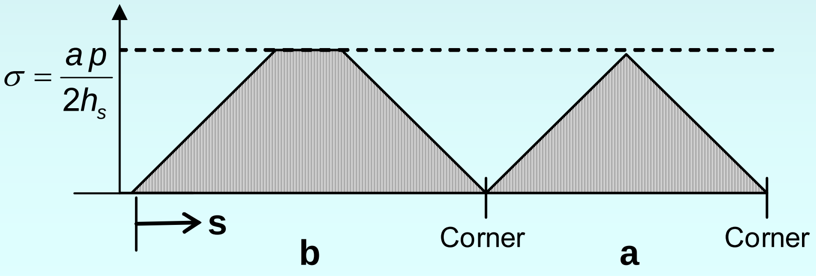
p surface load

a short edge length

$$\sigma_{centre} = \frac{a\,p}{2h_s}$$

Given a design stress σ_{design} (ETA) the formula can be re-arranged for a minimum width h_s to:

$$\longrightarrow \quad \min h_s \geq \left| \frac{a\,p}{2\sigma_{design}} \right|$$

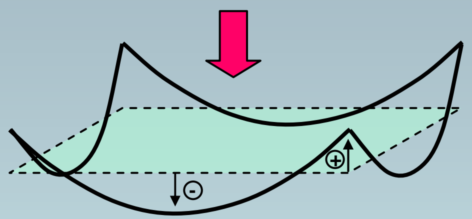


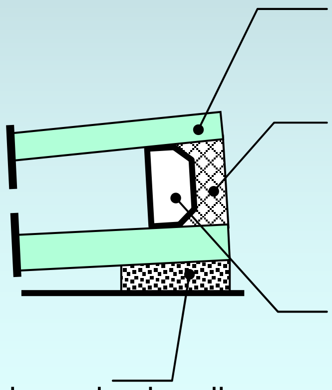
Assumptions of this formula:

- trapezoidal load distribution
- constant stresses in the bonding cross section

This Simplified Approach Neglects…

- Non-linear distribution of loading along the edges as supposed by plate theory (including sign changes at the corner area)
- Edge bending moments due to deformation of the glass panes (leading to stress variation in width direction of the bonding)
- Impact of stiffening and / or softening effects from:
  - façade elements
  - flexibility of spacer and supporting frame
  - the insulating sealing
- Geometry and bending properties of the glass panes which impact deformations to the bonding
- Effective mechanical properties of the adhesive in addition to the limit stress values





Alternative Approach to ETAG002 ...

- Research project “Untersuchung der Beanspruchung in der Klebefuge eines Structural-Glazing-Elements“ (Investigation of loading inside the bonding of a structural glazing element), Krüger, Völkel, Wohlfahrt, (FMPA, Stuttgart, 1992) :
  - Detailed investigation of SSG bond loading by means of FEA
  - Determination of material properties of the Silicone adhesive based on small representative specimens
  - Adequate consideration of 3D bonding geometry, sub-construction featuring finite bending stiffness and spacers
- Focus was put on:
  - Sign changes of stresses in corner areas
  - Dependency on stiffness of sub-construction
  - Dependency of load type and specimen geometry on material characteristics

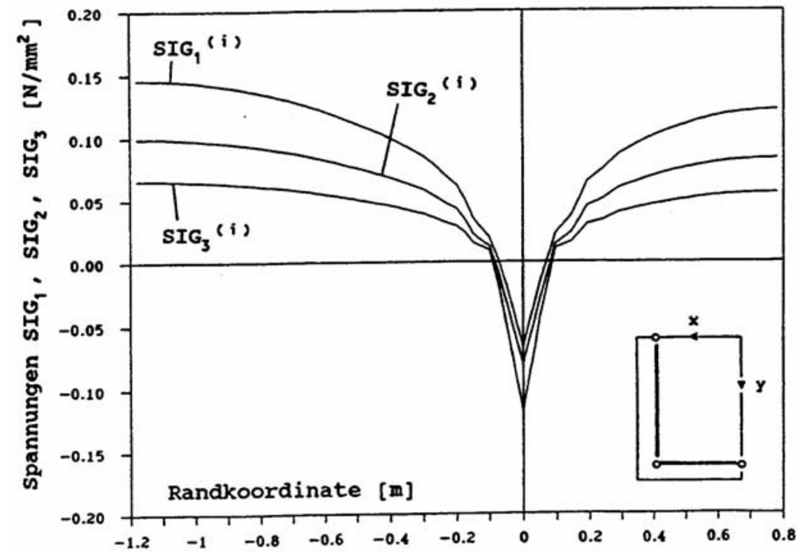


Bild 4.25. SIG_1 , SIG_2 , SIG_3 längs der inneren Kante der Fuge (Windsog, q_a =0,001N/mm²)

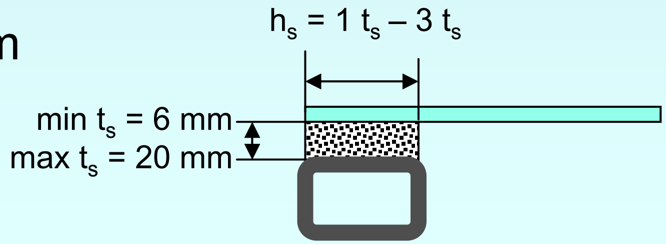
Picture from: “Untersuchung der Beanspruchung in der Klebefuge eines Structural-Glazing-Elements“, Krüger, Völkel, Wohlfahrt, (FMPA, Stuttgart, 1992)

Design Rules – Typical Silicone Adhesives for SSG

Two-component Silicone adhesive	European Technical Approval	Tension design stress $\sigma_{design, e}$	Shear design stress $\tau_{design, e}$	Shear design stress (creep) $\tau_{\infty, e}$
DC 993	ETA-01/0005	0.14 MPa	0.11 MPa	0.011 MPa
SG 500	ETA-03/0038	0.14 MPa	0.105 MPa	0.0105 MPa

1 MPa = 1 N/mm²

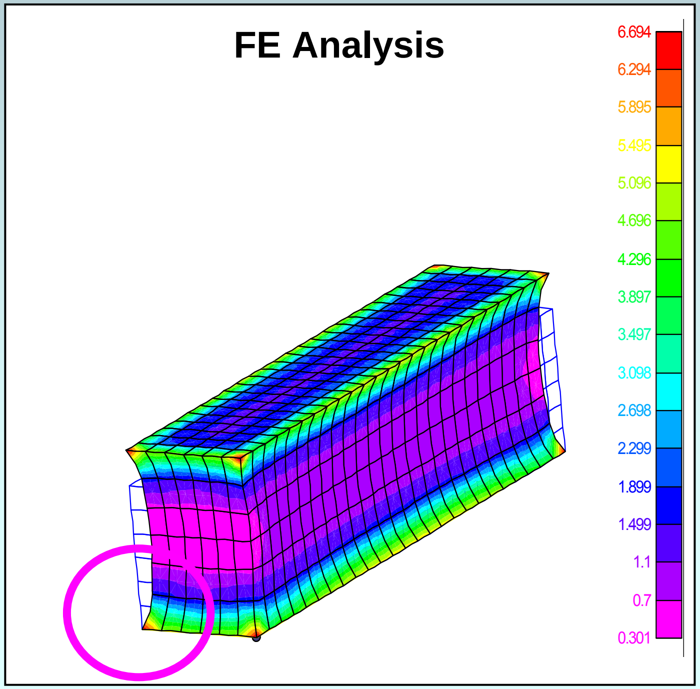
- Design stresses for dimensioning of structural silicone glazing joints are regulated in European Technical Approvals (ETA).
- The design stresses are determined based on H-specimen tests according to ETAG 002.
- The ratio of thickness (t_s) to width (h_s) is limited to values between 1:1 and 1:3.
- The minimum thickness is 6 mm, the maximum thickness (h_s) is 20 mm.
- The maximum width (h_s) is 20 mm.

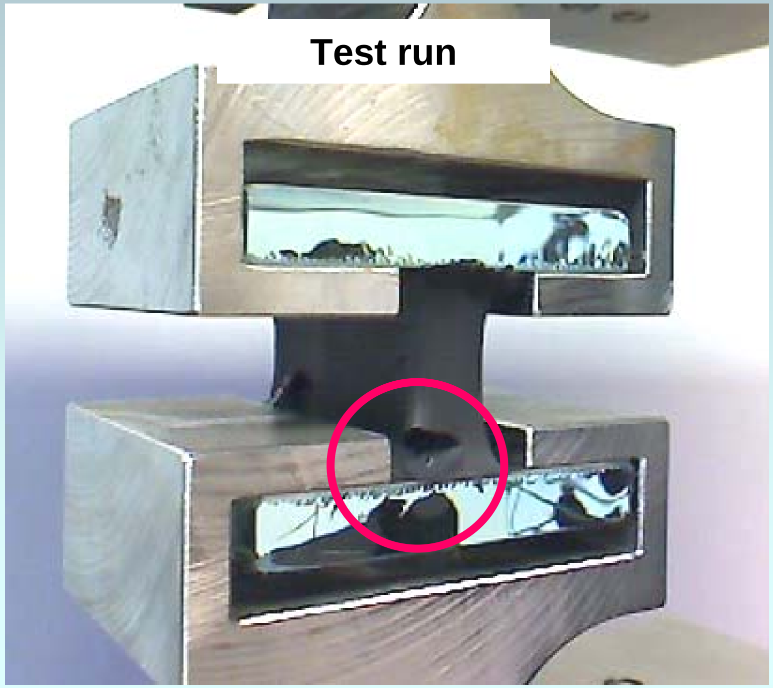


ETAG H-Specimen under Tension Loading

If Silicone is bonded to a significantly stiffer material, the lateral contraction at the interface is suppressed. This leads to complex 3D stresses and also to a stiffer behavior in comparison to uniaxial tests.

The failure of the H-specimen according ETAG 002 is typically affected by stress peaks at the corners.





Test Run of ETAG H-Specimen under Tension

The test shows the failure mechanism in accordance with FE Analysis

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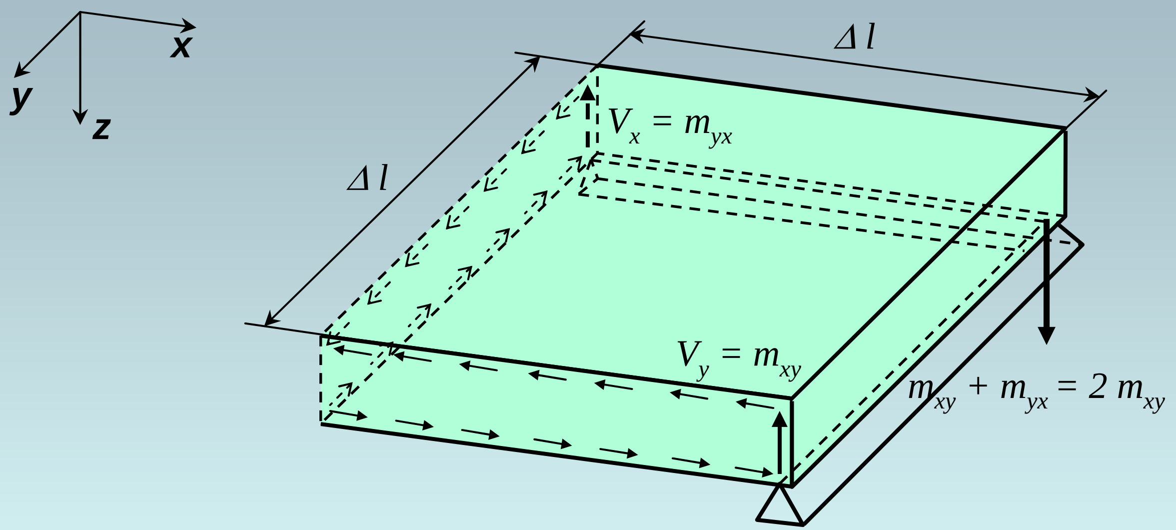
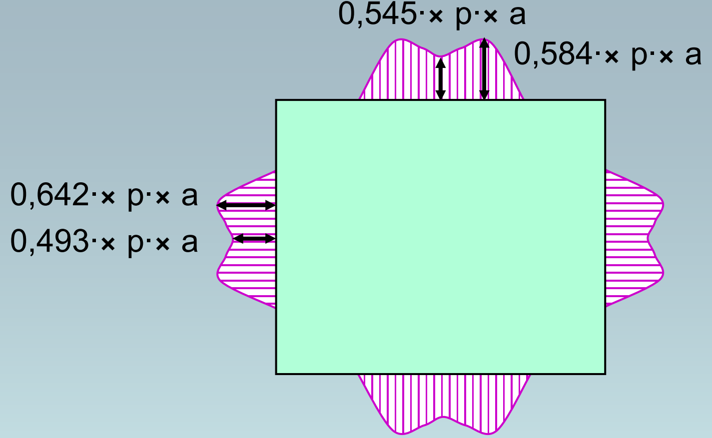
Corner Forces of Simple Supports – Plate Theory

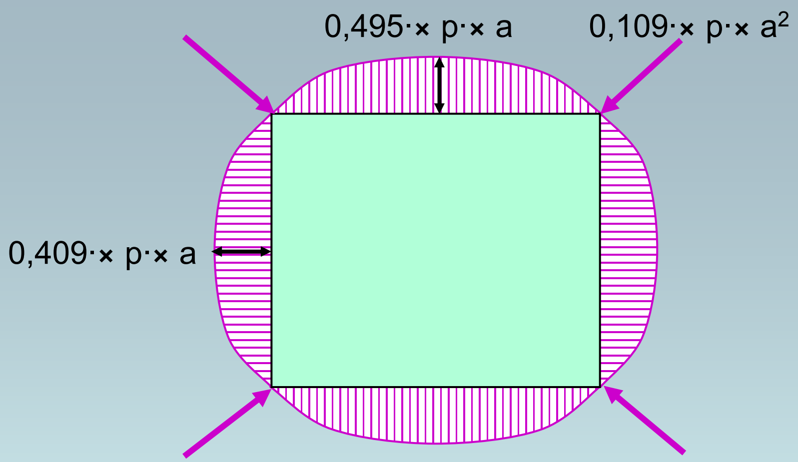


For force balance in vertical direction a concentrated load is generated from twisting moments (e.g. due to wind loads).

For isotropic plates: $m_{xy} = m_{yx}$. The related concentrated corner reaction force is $F = m_{xy} + m_{yx} = 2m_{xy}$.

Concentrated Corner Loads





A 'compression-only' supported plate reacts with lift-off of corners and thus avoids concentrated corner loads.

In a structural silicone glazing system this phenomenon is not the case !

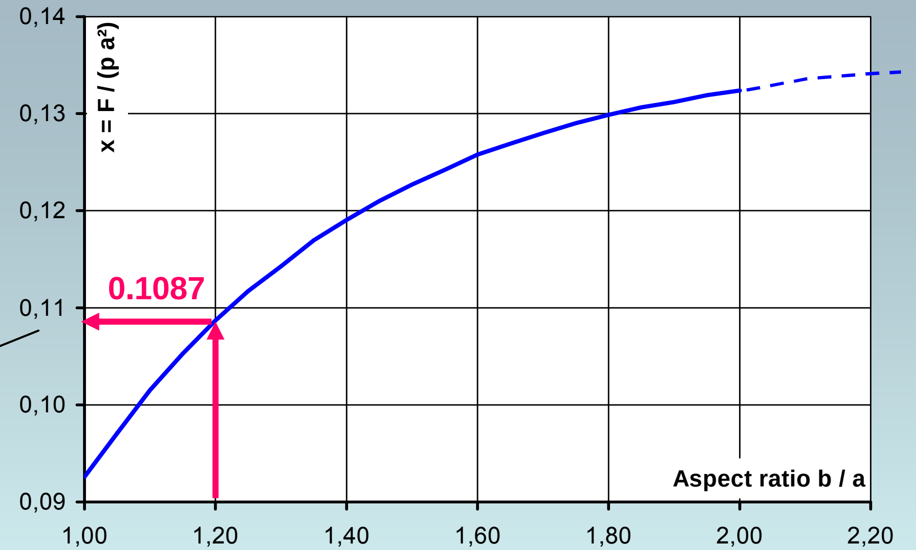
A fully supported plate reacts with concentrated corner loads for constant pressure loading.

In case of a flexible support as in structural silicone glazing systems, it can be expected that the impact of corner loads is slightly reduced by load transfer from the corners into the edges. This is due to the flexibility of the bonding.

Corner Loads in Civil Engineering

Several sources provide tabulated values x for determining the corner load F as a function of the aspect ratio of long side b to small side a.

$$F = p \cdot a^2 \cdot x$$



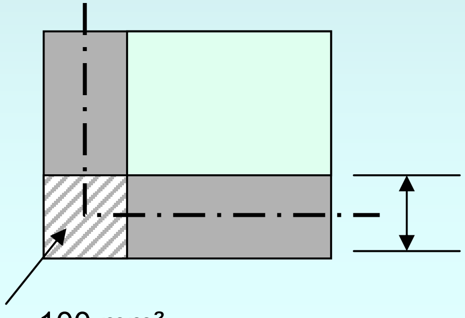
Example for panes with h_s= 10 mm:

a = 1.25 m
b = 1.50 m

b/a = 1.2

x = 0.1087

F = 2.24 x 1.25² x 0.1087 = 0.38 kN



$\sigma_{A, Corner}$ = 380 / 100 = **3.8 N/mm² >> 0.14 N/mm²**

But it can also be assumed:

- This load is introduced less concentrated in the corner area.
- Thus, the peak corner loading is reduced due to the flexibility of silicone adhesive.

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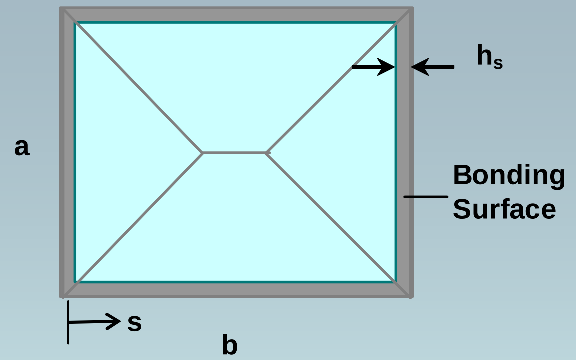
Parameters for Numerical Investigations

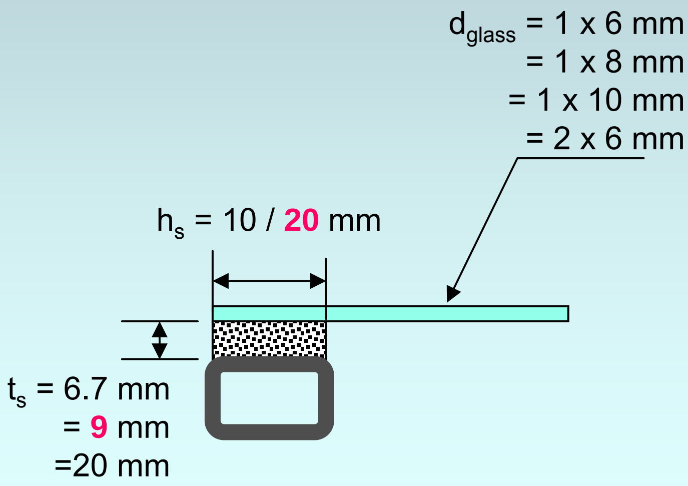


Sizes	t_s = 6.7 mm	**t_s = 9 mm**	t_s = 20 mm
h_s = 10 mm		+	
h_s = 20 mm	+	**+ (default)**	+

The pressure load ‘p’ acting on the glass panes was adjusted in order to exactly fulfill the ETAG 002 sizing formula.

This load was defined as either pressure or suction acting on the glass pane.

More focus is given on pressure loads due to the expected tension load peaks in the corners. This is more critical for the adhesive.



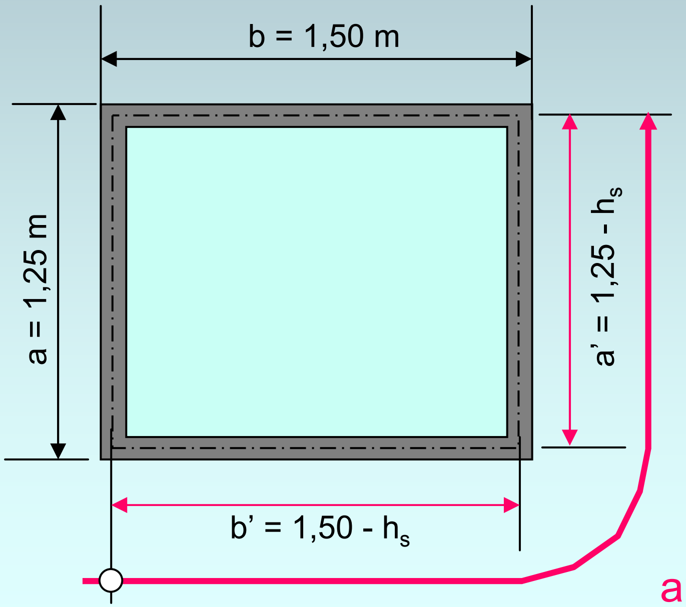
Loads on Investigated Panes

Formula according ETAG 002: $\sigma_{centre} = \frac{a\,p}{2h_s}$

Re-arranged for the load p: $p = \frac{2 \cdot h_s \cdot \sigma_{design}}{a}$

h_s = 10 mm → p = 2,24 kN/m²

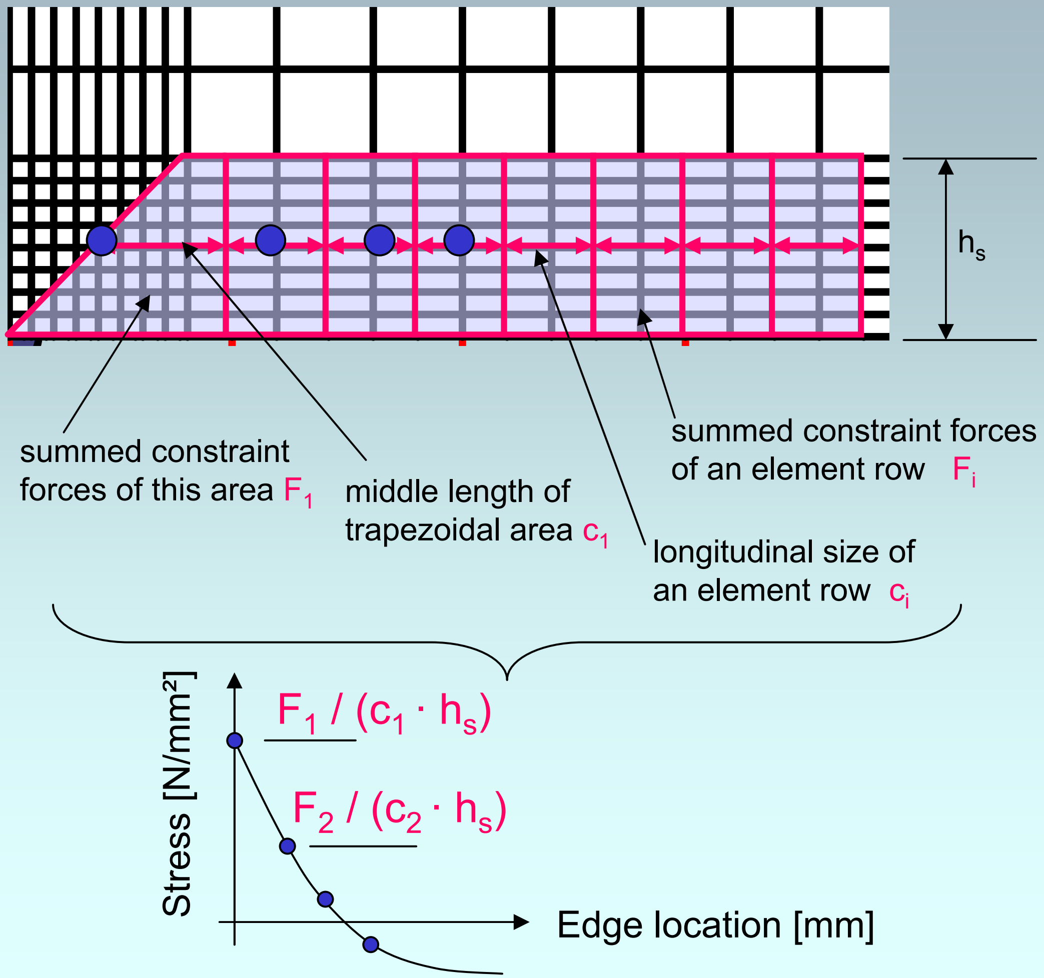
h_s = 20 mm → p = 4,48 kN/m²



Under this preconditions it should be expected that the stresses of the adhesive are in an allowable range.

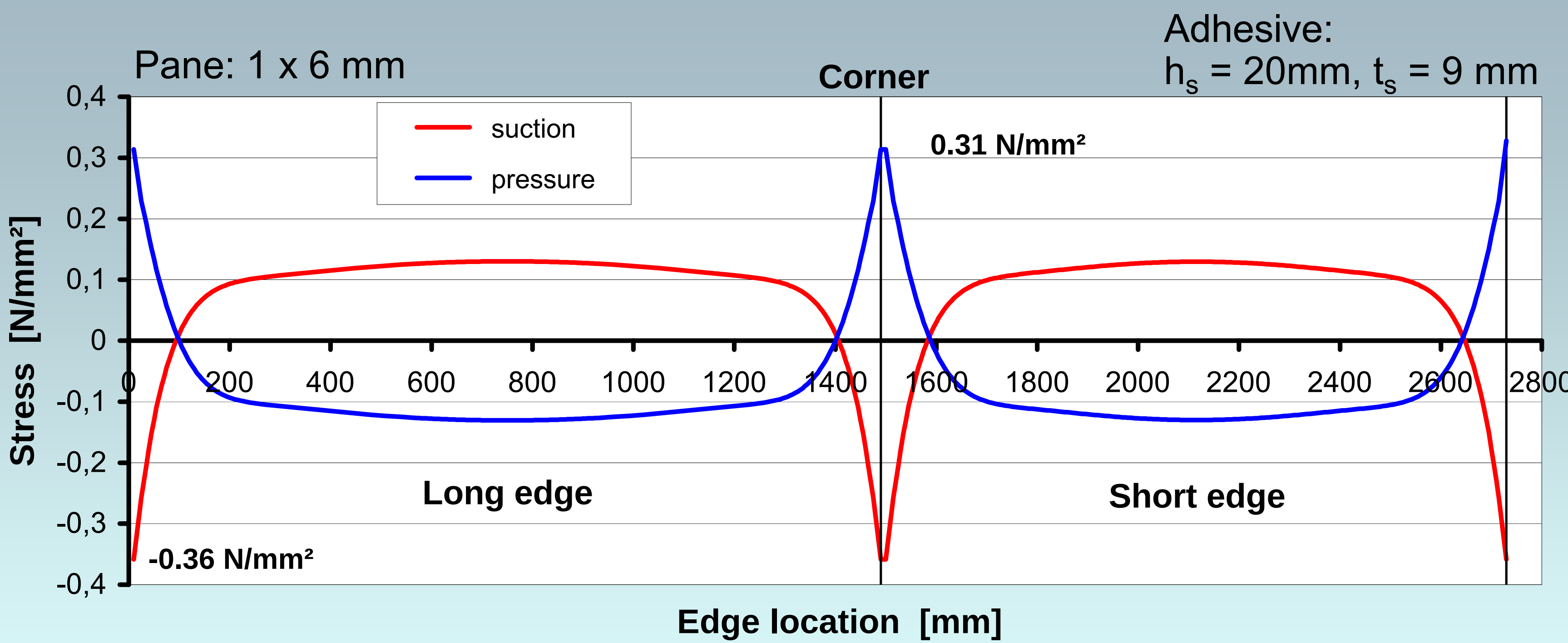
a' and b' (reduced by the bonding width) are used for stress plots!

Method of Sampling Averaged Stresses from FEA



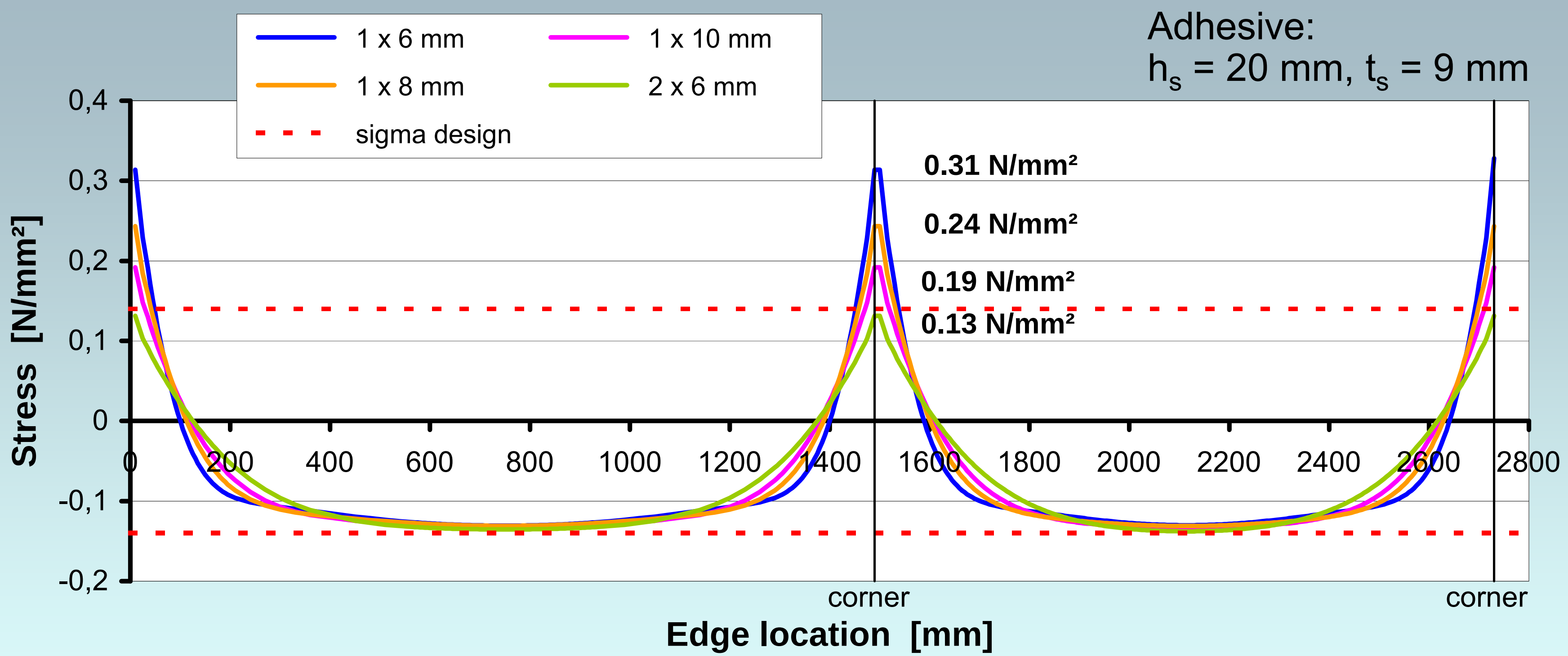
- For comparison with ETAG 002: averaged stresses across bonding geometry are required
- Averaging procedure
  - In bonding corners:
    The reaction forces are summed up and related to the area of the corner
  - Along the bonding:
    The reaction forces are summed up for each element row (F_i) and related to areas of element lengths (c_i x h_s) in longitudinal direction
- The hereby obtained (1D) stress values are plotted along the bonding geometry.

Baseline Results for Suction and Pressure Load Cases



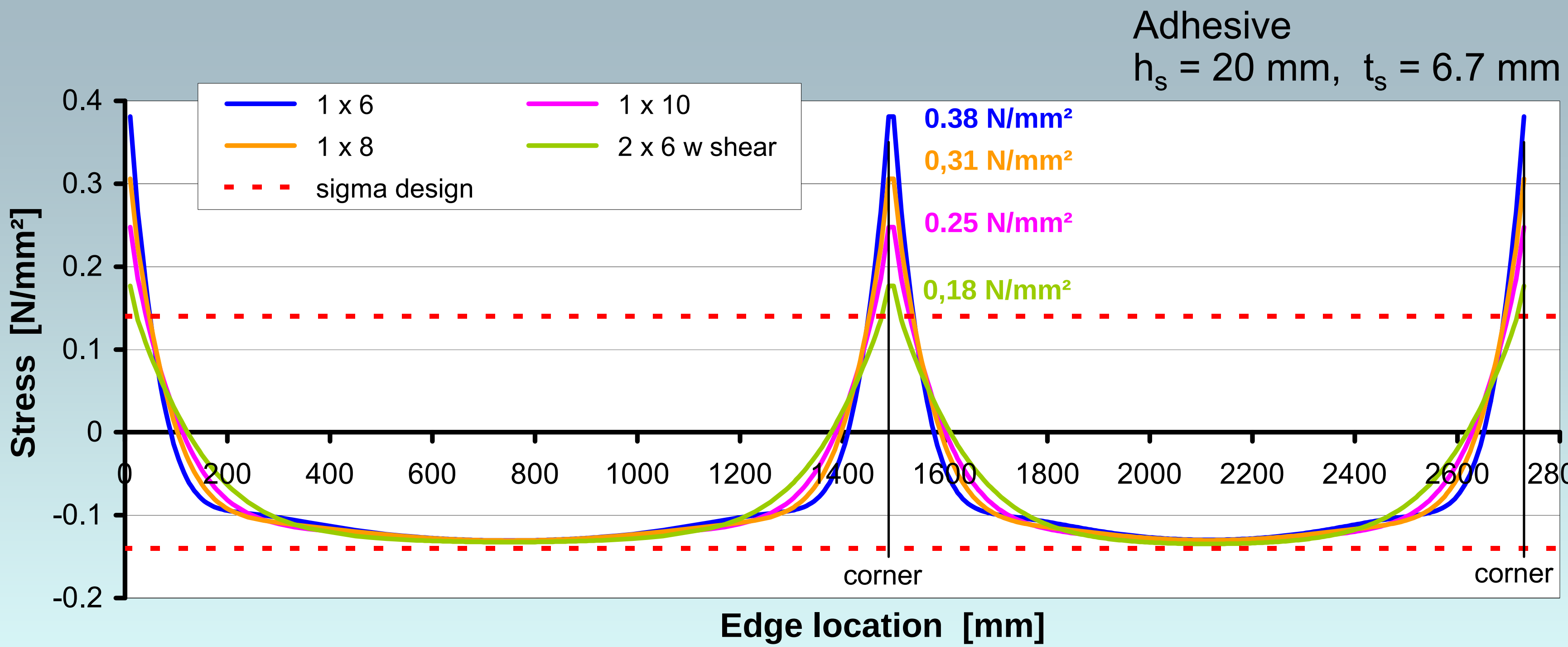
- Sign changes of bonding stresses are observed in the corner areas as expected from plate theory.
- The peak stress levels in the corner areas exceed the stress levels along the edges.

Impact of Glass Thickness on Corner Loading



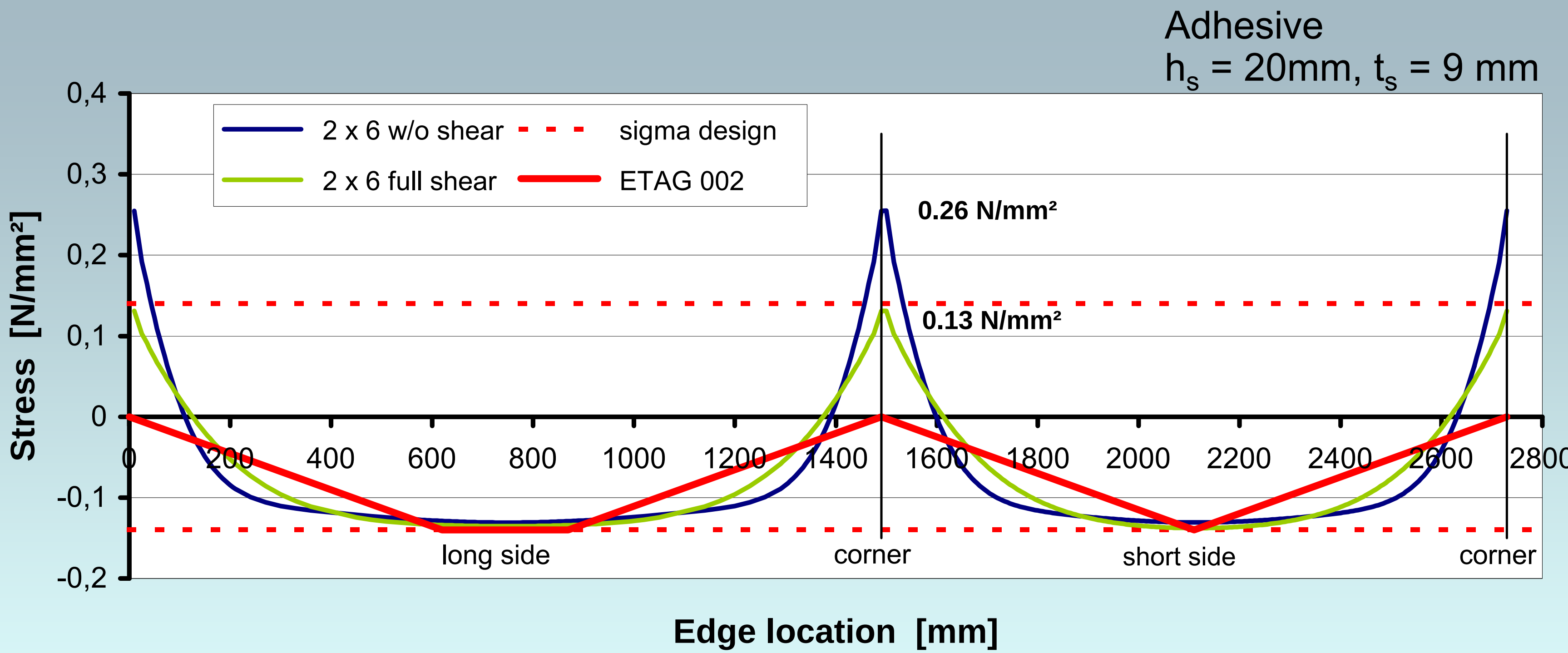
- Thinner glass panes show larger corner stresses !
- The lower bending stiffness of the glass pane is less effective to transfer parts off the corner loads into the neighbouring edge area.

Impact of Glass Thickness for Thinner Bonding Geometries



- For lower adhesive thickness the peak corner stresses increase !
- Lower adhesive thickness leads to stiffer bonding characteristics. Again, load transfer from the corners into the neighbouring edge areas is less effective.

Composite Behavior of Interlayer (PVB)

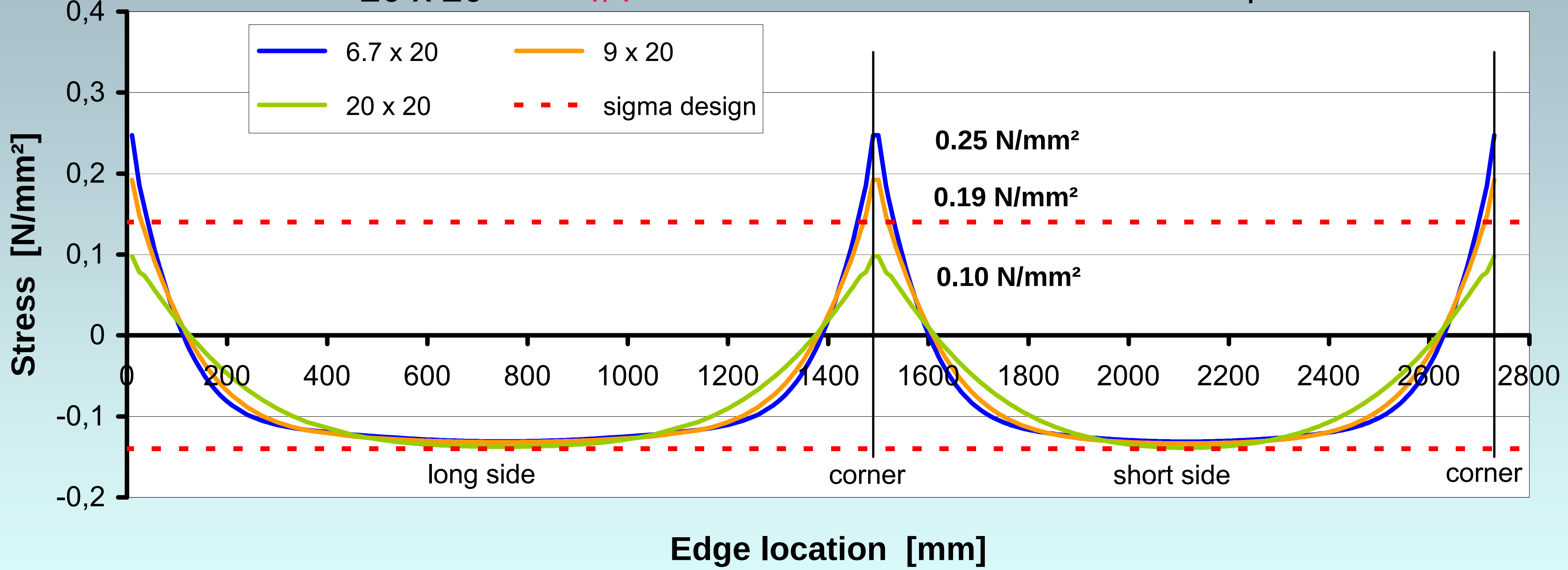


- In case of a fully composite behavior of interlayer (full shear) the resulting high glass bending stiffness leads to low corner loads.
- The corner loads are doubled in case of missing composite behavior (w/o shear) for this case.
- This result is in line with the parameeter variation of the glass thickness.

Variation of Adhesive Thickness

Adhesive: 6.7 x 20 → 1/3
t_s / h_s 9 x 20 → 1/2,2
20 x 20 → 1/1

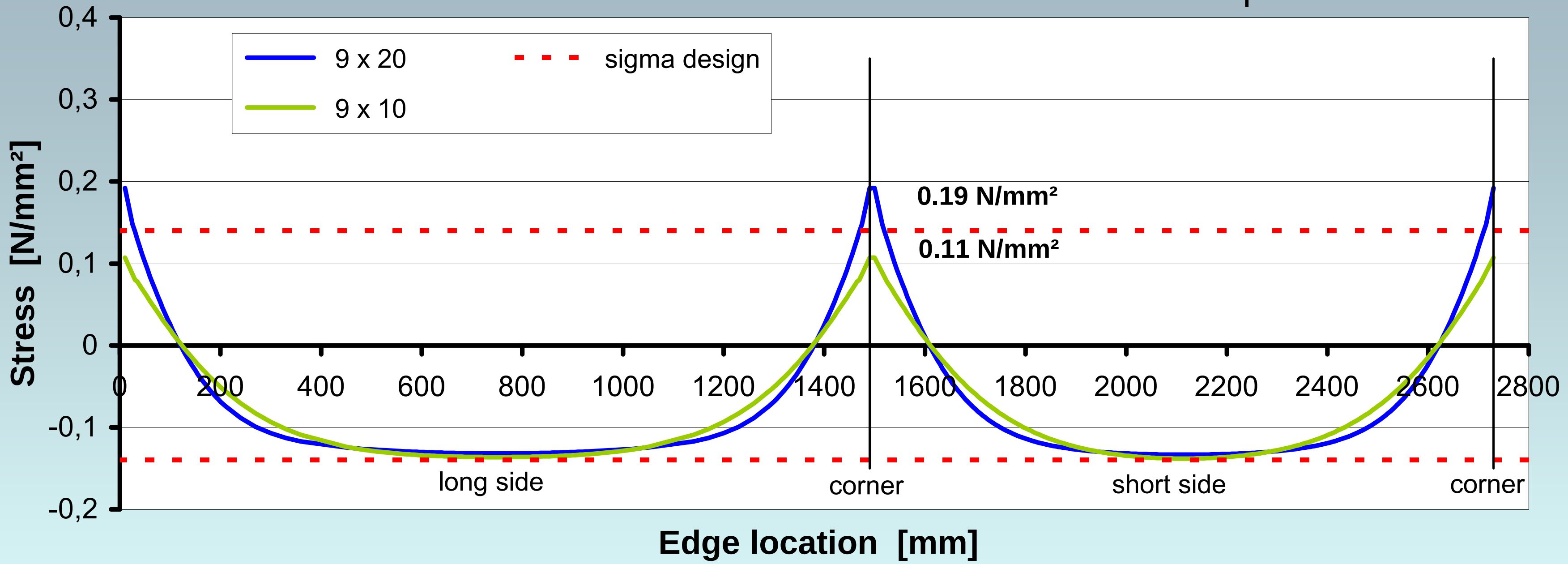
Glass pane: d = 10 mm



- Higher corner stress levels occur for lower adhesive thickness
- The lower the adhesive thickness, the higher the stiffness of the bonding
- Stiff bonding designs are less effective in the load transfer of corner loads.

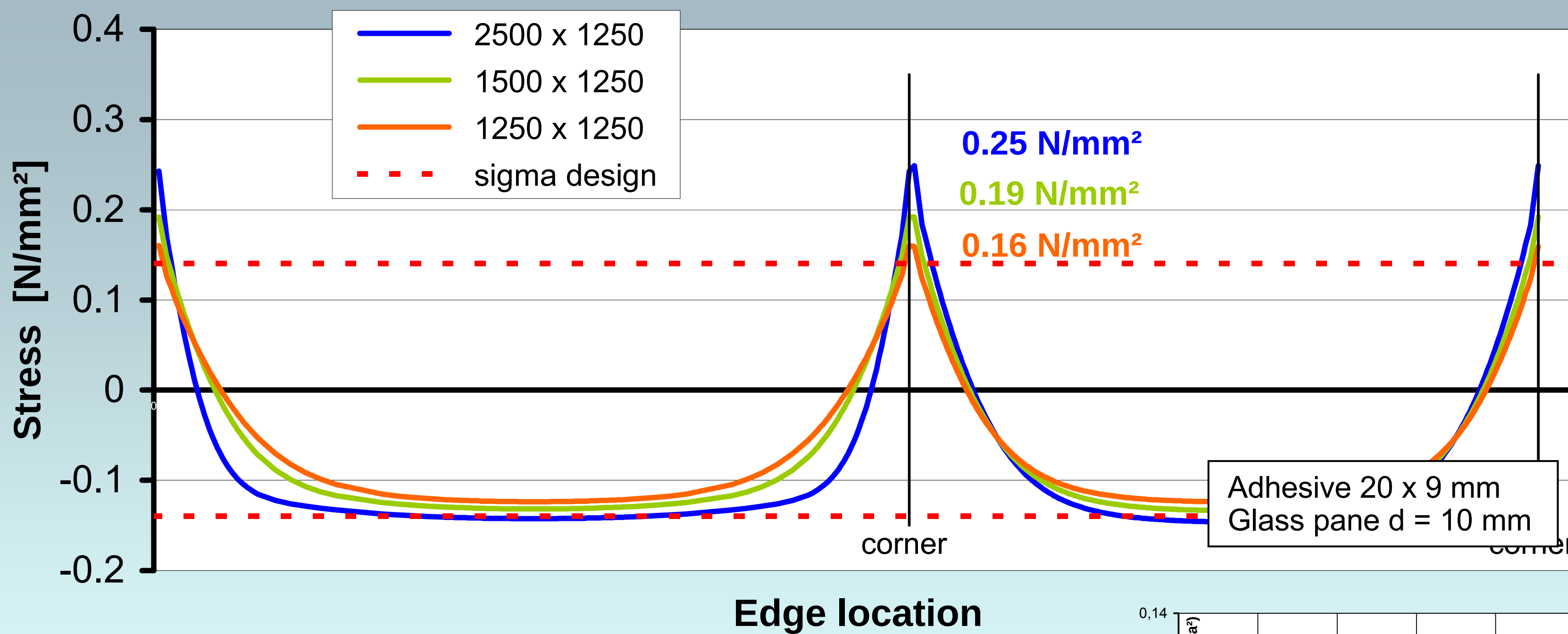
Double Load by Double Width ?

Glass pane: d = 10 mm

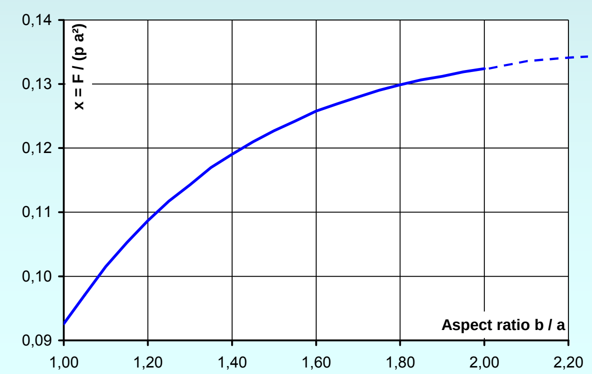


- The corner stresses are significantly higher (72% !) when the adhesive width h_s is doubled for double loading (→ impact on sizing).
- The broader the adhesive is, the higher is the effective stiffness of the bonding. This effect is due to the suppression of lateral contraction.
- As stated before stiff bonding designs are less effective.

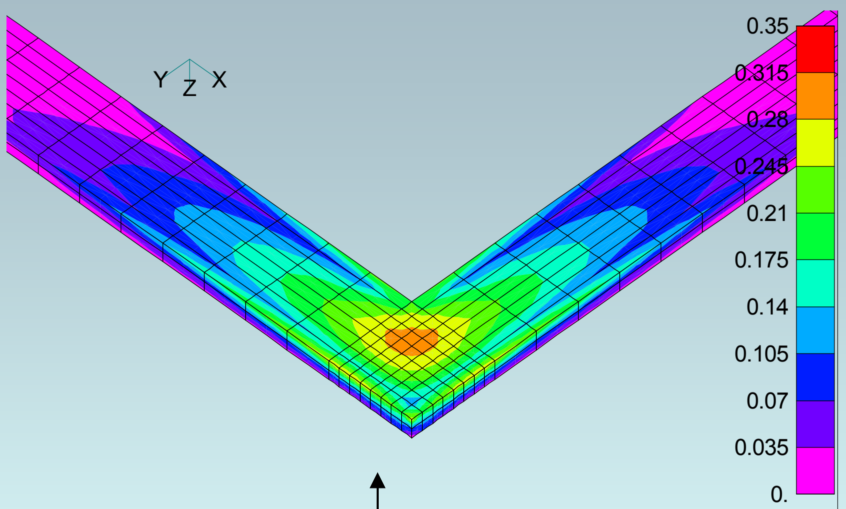
Stress Distribution for Various Glass Aspect Ratios



- The higher the aspect ratio the higher are the stress peaks in the corners.
- This result is in accordance to the dependency of the concentrated corner force as function of aspect ratio.

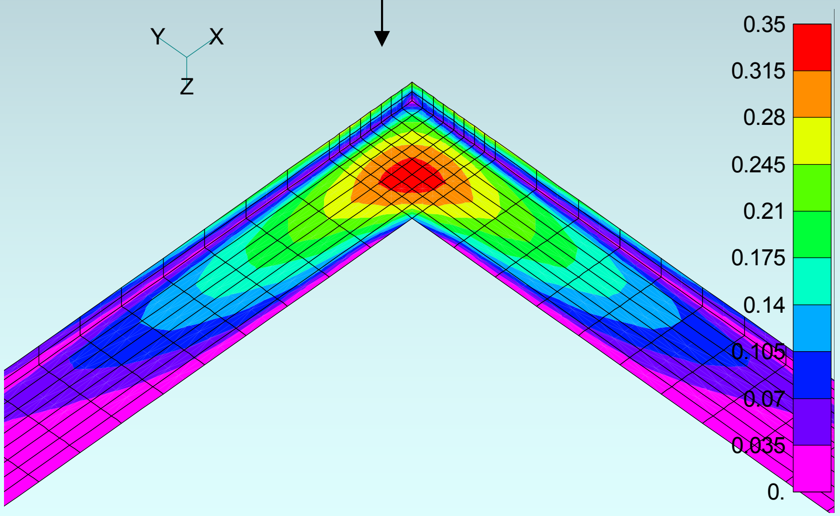


Stress Distribution in Adhesive



Normal corner stress distribution,
top view (glass side)

Normal corner stress distribution,
in the middle plane of adhesive



Adhesive
h_s = 20mm, t_s = 9 mm

Comparison of Averaged Stress to Local Stress

Glass pane	Averaged corner stress [N/mm²]	FEA corner stress [N/mm²]	FEA glass stress [N/mm²]
1 x 8 mm	**0.31**	**0.52**	37
1 x 10 mm	**0.25**	**0.42**	24
2 x 6 mm w/o shear	**0.32**	**0.55**	33
2 x 6 mm w shear	**0.18**	**0.29**	14

FEA max. corner stresses are approximately 70% higher than the averaged stresses!

All stresses are obviously beyond the allowable stresses of 0.14 N/mm² !

Contents

Conclusions

- Numerical parameter studies based on FEA have been performed for structural bonding designs. Special focus was given on concentrated corner loads as expected by thin plate theory.
- The Finite Element Analyses showed that the effect of corner loads significantly influences the stress distribution in the corner zones.
- This effect leads to averaged stresses in the corner area which can be higher than nominal design values according to ETAG 002.
- The corner stresses increase for
  - increasing aspect ratios of the glass panes
  - increasing glass bending flexibility
  - increasing bonding stiffness
- As permanent corner stresses will be introduced by cold bending procedures the corner stresses due to pressure loading might impact the durability of cold bent glass.

The End

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