Development and Test Logics for Structural Silicone Bonding Design and Sizing

A. Hagl GmbH, Expertisen. Presenter: Dipl.-Ing. A. Hagl

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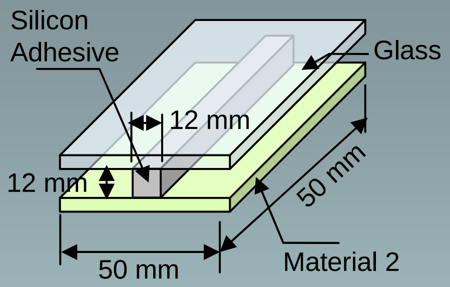
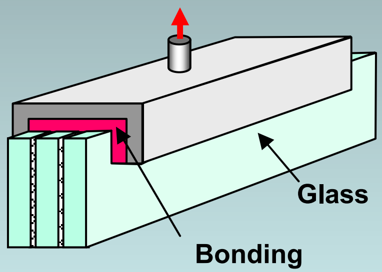
* ETAG 002: Guideline for Structural Silicone Glazing

Why Thinking about Test Logics for Structural Bonding Designs ?

- **Only a simplified and narrow design window exists for simple bonding design – ETAG 002**



- **For complex bonding designs (such as U-type or point-wise bondings) no design-rules exist.**



- **Challenge is:**
  - **Complex material behavior – hyperelasticity, Mullins, ...**
  - **Advanced non-linear analysis tool is required**
  - **No rules exist for (experimental) determination of limit stresses or limit strains**
  - **What about (definition of) safety concept towards design stress (or design strain)?**

Tests for Elastic Characteristics beyond ETAG 002

Comparing Tensile Tests on Dogbone and ETAG Specimen

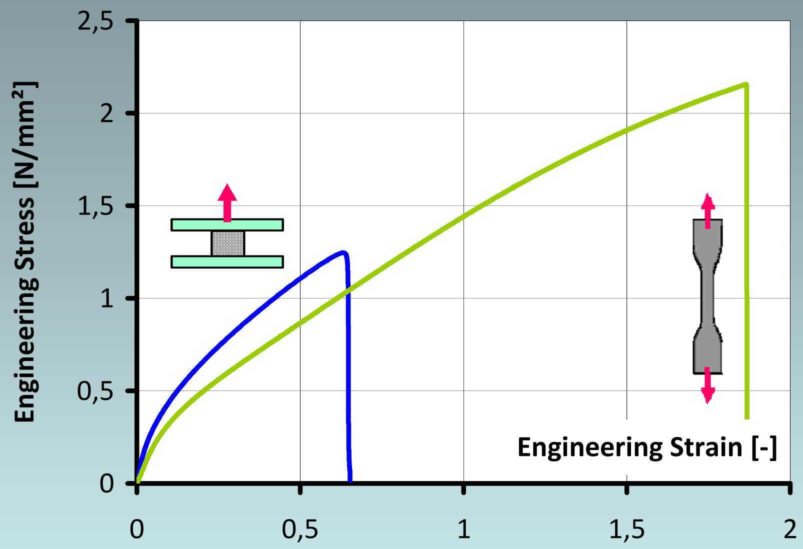
Boundary conditions are dominating!

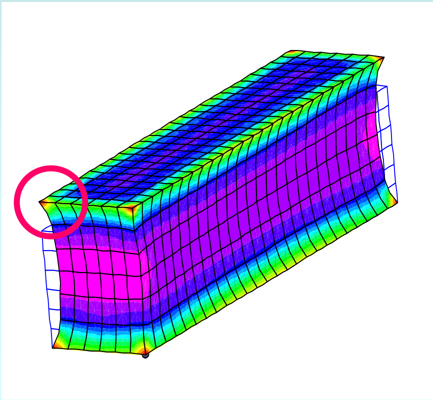
The higher the suppression of lateral contraction:

- **the lower is the ultimate stress**
- **the higher is the stiffness**

Higher suppression of lateral contraction (on stiff plates) leads to:

- **non-uniform stress (3D)**
- **stress-concentrations in corners and edges of the specimen**
- **earlier failure compared to dog-bone tests**

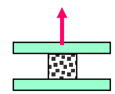
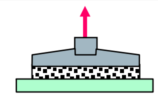
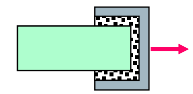




Tests for Elastic Characteristics beyond ETAG 002

Elastic Characteristic of Bonding Geometries

Typically, tensile loading is most critical and most complex (e. g. compared to shear)

	specimen		representative application cases		
Specimen Type	 Dog-Bone Specimen	 ETAG H-type Specimen	 Planar Round Point Support	 U-type Point Support	Trend
Stress and strain field	Uni-axial (1D)	Complex (3D)	Complex (3D)	Complex (3D)	
Strain $\varepsilon_N = \Delta l / l_0$	1,19	0,82	0,08	0,06	↘
Stiffness σ_N / ε_N	0,84	1,21	12,9	16,9	↗
Stiffness related to dog-bone	1	1,44	15,4	20,1	↗

Increasing suppression of lateral contraction due to less free surface →

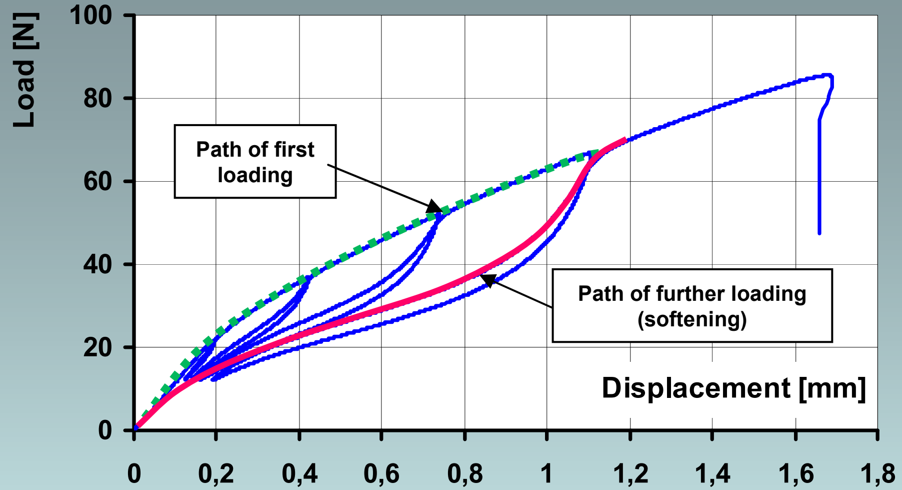
Different silicone geometries with increasing grade of suppression of lateral contraction under nominal stress 1 N/mm² show:

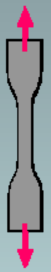
- **lower strain**
- **higher stiffness**

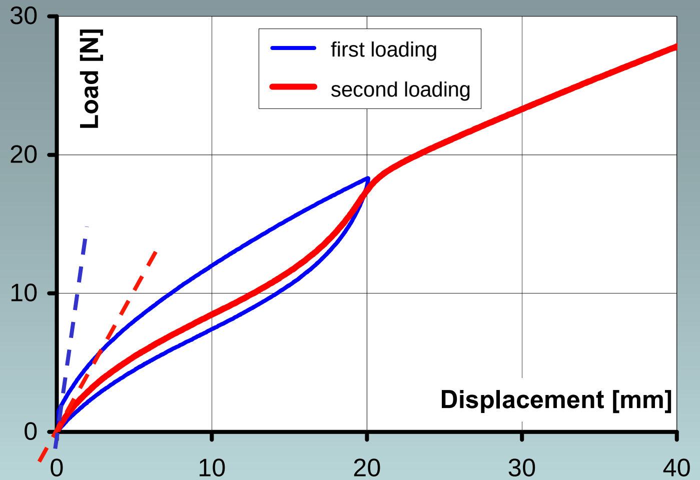
Effective elastic characteristic is depending on application case ⇒ small sample tests

Tests for Elastic Characteristics beyond ETAG 002

Mullin's Effect – Impact on Test Results and Interpretation







Mullin's effect is due to release of physical connections between molecule-chains

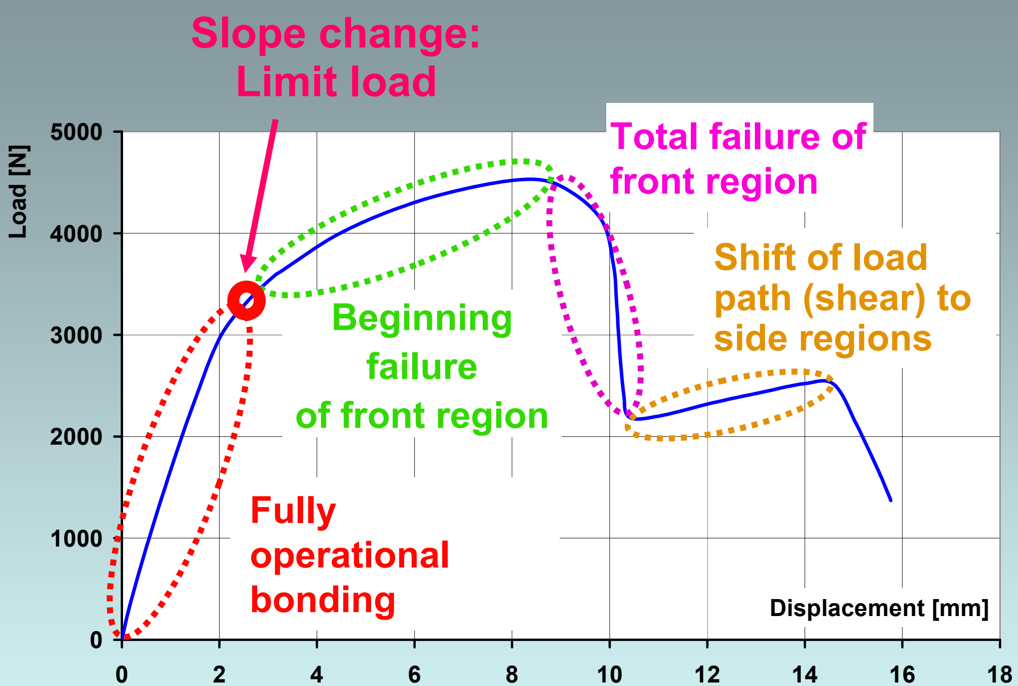
- ➢ **Material properties recovered if amplitudes of former load cycles are exceeded**
- \- **Sizing linked to undegraded material properties assuming a dominant (i.e. critical) load direction**

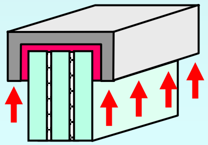
Impact on test procedure

- ➢ **Care has to be given for handling of specimens ⇒ in case of mistreatment: softening**
- ➢ **The Mullins effect leads to a wrong assumption of initial stiffness (e.g. Young's Modulus) and therefore to a potential discrepancy between test results and FEA.**

Tests for Failure Mechanisms in Addition to ETAG 002

Limit Load – U-Type Bonding under Tension





3 x 12 mm
length 50 mm

Depending on application case:
Bonding design important for failure
⇒ needs small sample tests

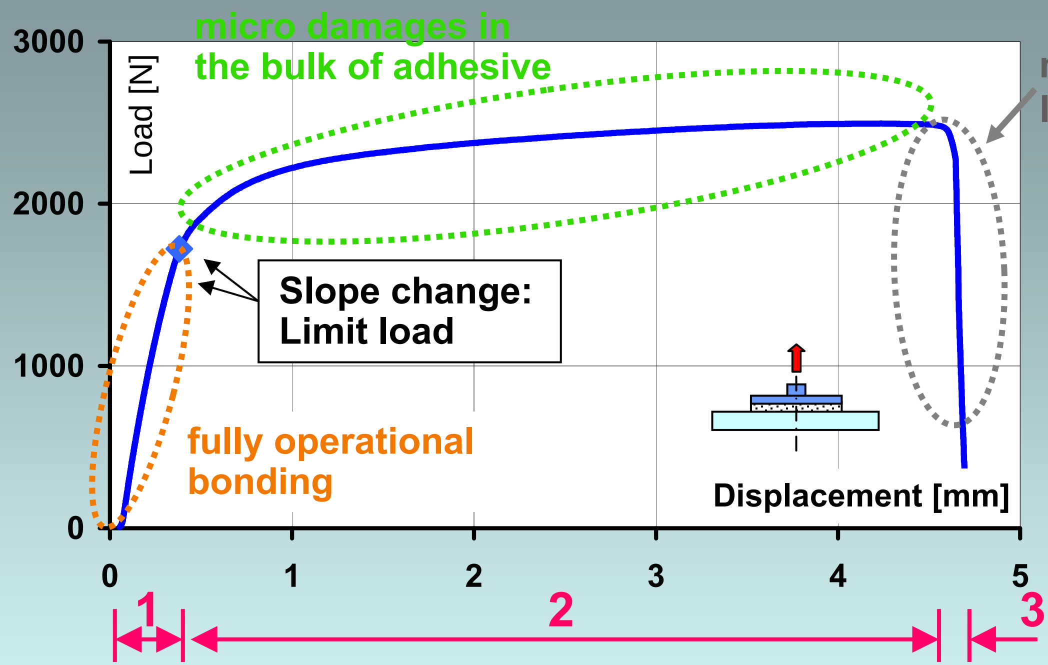
Complex failure mechanism due to different bonding regions

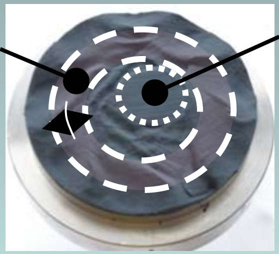
- **fully operational bonding at the beginning from 0 to 2,3 mm**
- **beginning failure of front region between 2,3 and 8.5 mm**
- **total failure of front region between 8,5 and 10,2 mm**
- **total failure incl. side regions > 14,2 mm**

Post failure can be designed by bonding geometry (ratio front / side)

Tests for Failure Mechanisms in Addition to ETAG 002

Limit Load – Planar Point Support under Tension





1 Beginning of macro cracks at an inner circle

2 Crack-progress to inside and outside

3 Finally the core fails

Comparable failure pattern to U-type bonding

- fully operational bonding at the beginning	from 0 to ≈ 0,4 mm
- beginning failure of front region	between ≈ 0,4 and 4.5 mm
- total failure, as no side region exists	> 4,5 mm

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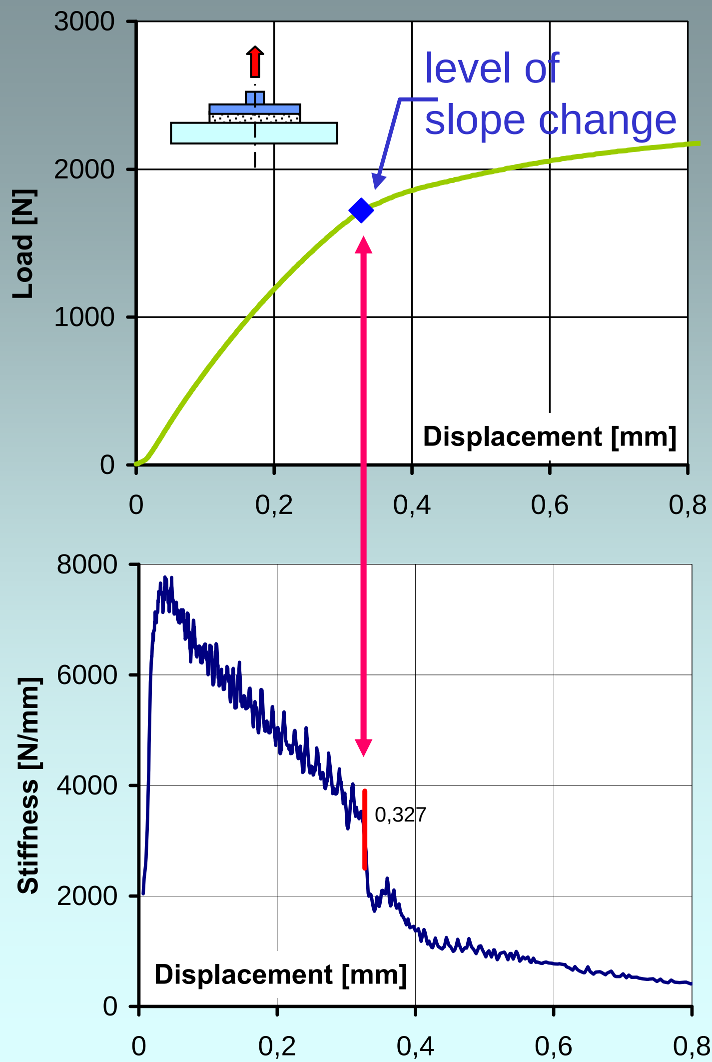
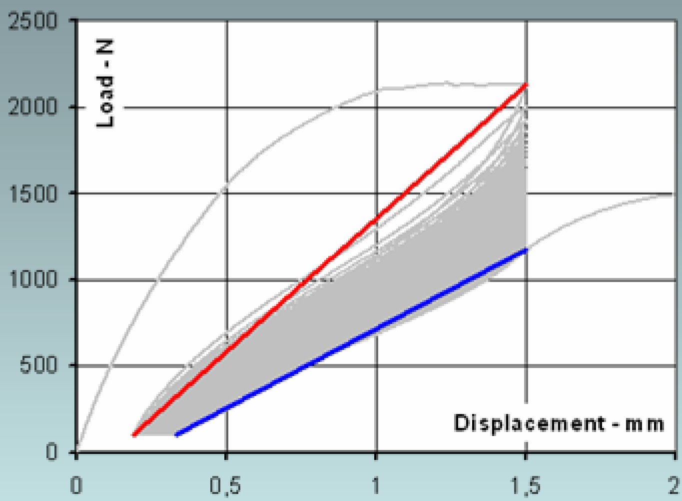
Useful Limit Load Level – How to get it?



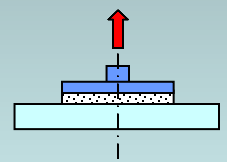
- **The sudden loss of stiffness indicates a reasonable limit of loading of a bonding geometry.**
- **This phenomenon is also observed by other geometries, e.g. U-type bonding.**
- **The point of loss of stiffness has been predicted as the beginning of damage inside of the adhesive.**
- **The stress level which is corresponding to this level is: Limit stress level**
- **Cyclic tests verified this thesis of beginning failure.**

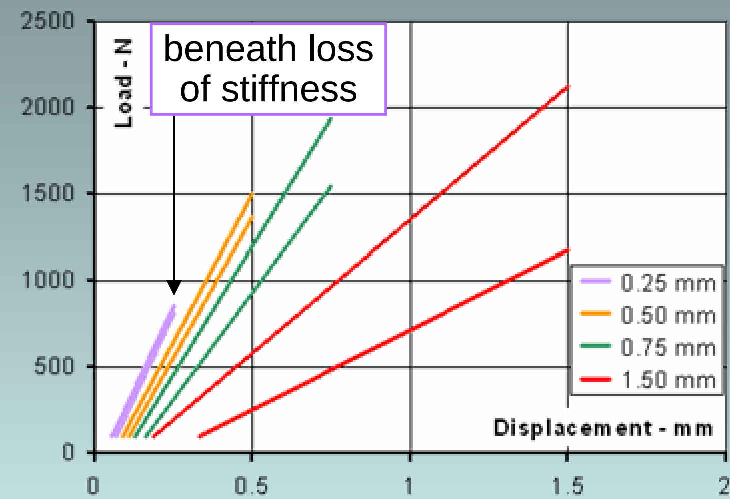
Material Failure Indicated by Cyclic Loading Tests

Limit Load Level Definition Motivated by Load Degradation



Cyclic tests on different displacement level on round test specimen





For the displacement level of 1.5 mm we observe a significant degradation, comparing gradients of first cycle to last cycle.

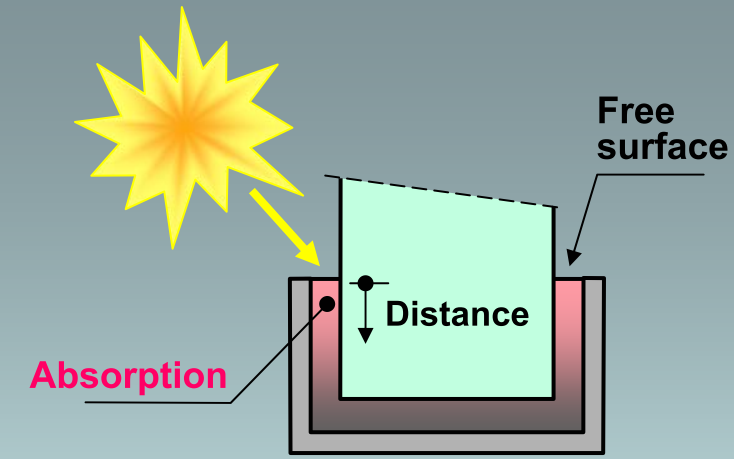
The reduction of the slopes depends on the displacement level.

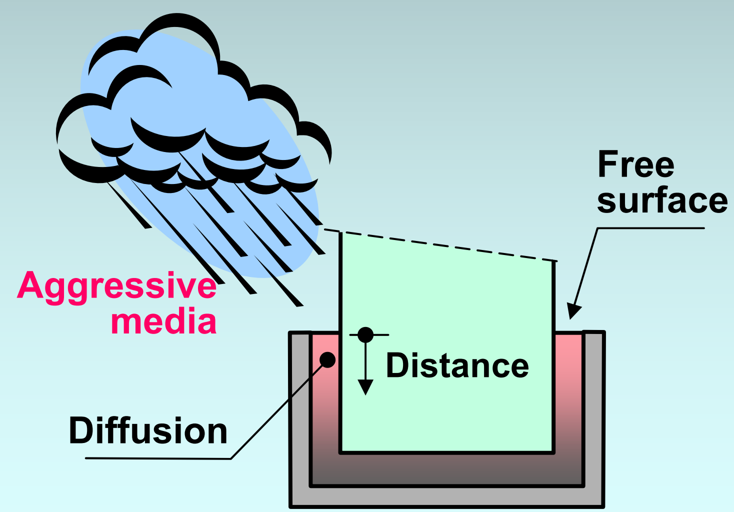
The higher the displacement level :

- **the higher the decrease of slopes**
- **the higher the material degradation**

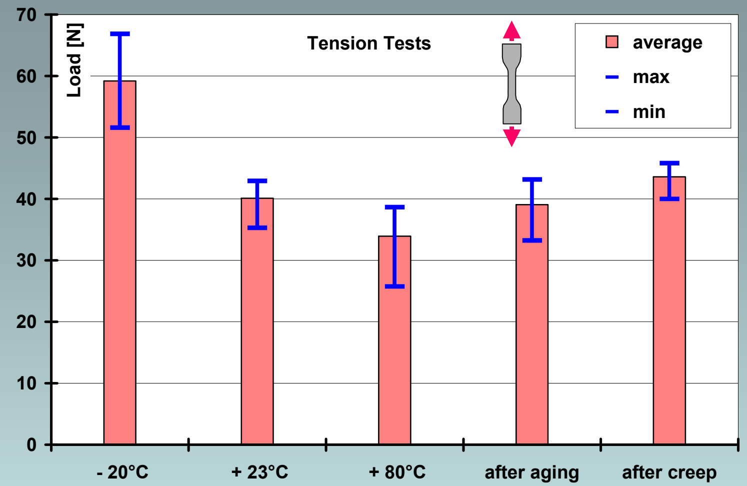
Safety Factor: Effects of Environmental Condition

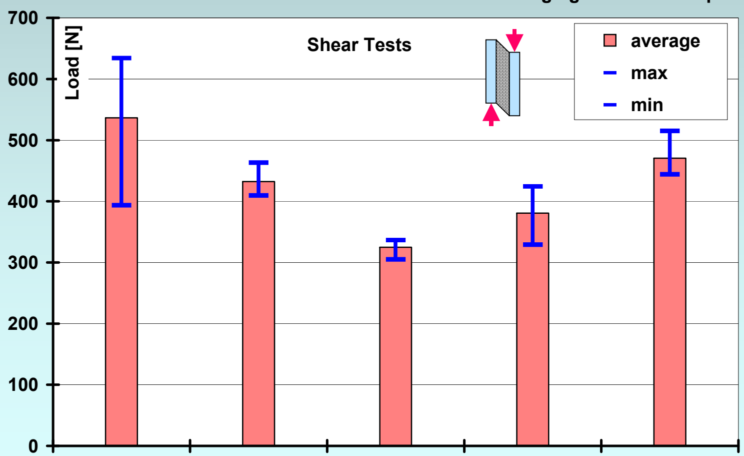
- **Safety factor needs to cover durability aspects**
- **Level of environmental impact of aggressive media and solar radiation is a function of distance below the free surface of adhesive.**
- **Physical principles are:**
  - **Absorption of radiation**
  - **Diffusion of aggressive media**
- **Highest impact on damage is expected for the free surface and will decrease with increasing distance inside the adhesive.**
- **Stress level in vicinity of free surface has to be limited.**





Safety Factor: Temperature and Aging





- **Safety factor needs to cover temperature and aging**
- **Strength of specimen is slightly affected by aging or creep compared to unaged test under room temperature (23°C)**
- **Specimen strength is significantly affected by temperature – strength reduces at an increasing temperature**
- **Results between tension and shear are in general agreement**

Source of data: Geklebte Verbindungen im Konstruktiven Glasbau, Final Research Report, BMBF Projekt, AIF-Nr.: 1755X04, 2007

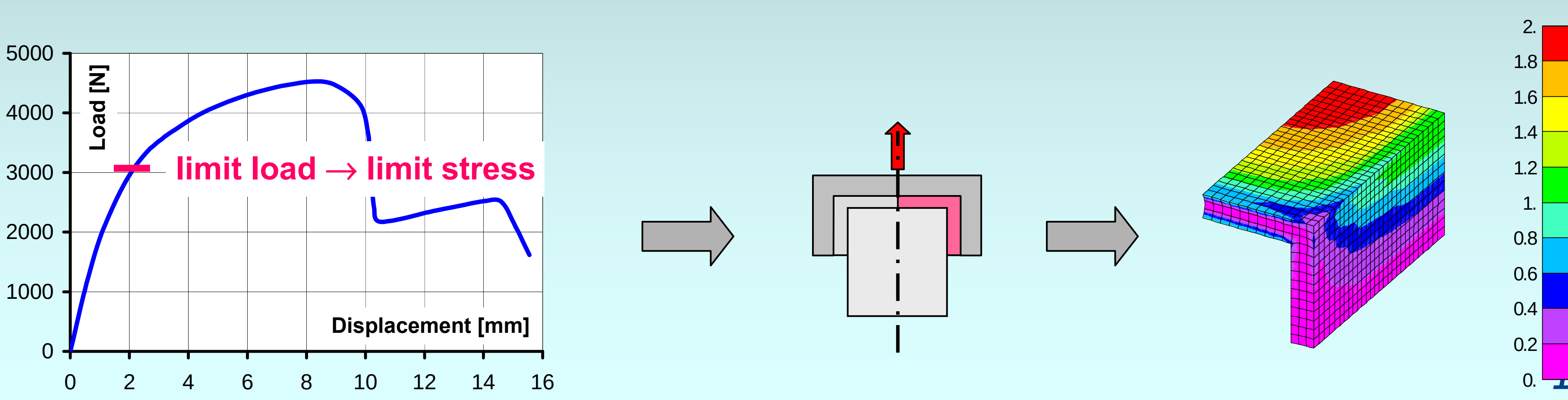
Design Stress – Pragmatic Approach (Local Safety Concept)

Limit stress under limit load for a complex bonding geometry adapted from experiments and FEA (Cauchy Stress) — $\sigma_L \approx$ **2,00 N/mm²**

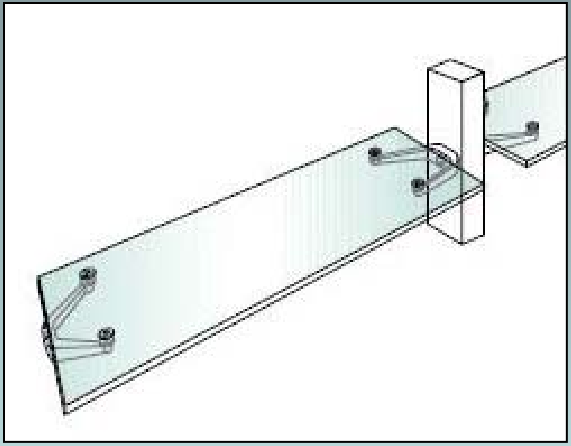
With safety level of ETAG 002: (2,0 / γ) — $\gamma = 6$ — $\sigma_D =$ **0,33 N/mm²**

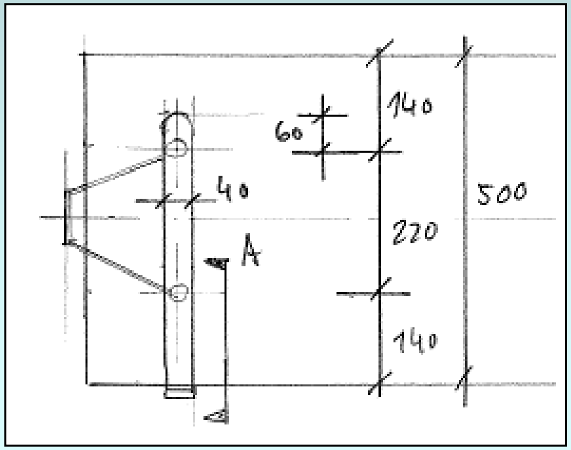
Design stress for local optimized concept:

Safety factor for short term loads (wind)				
	Inside bonding	$\gamma = 5$	max $\sigma_D =$	0,40 N/mm²
	Edge area < 10 mm	$\gamma = 7$	max $\sigma_D =$	0,29 N/mm²

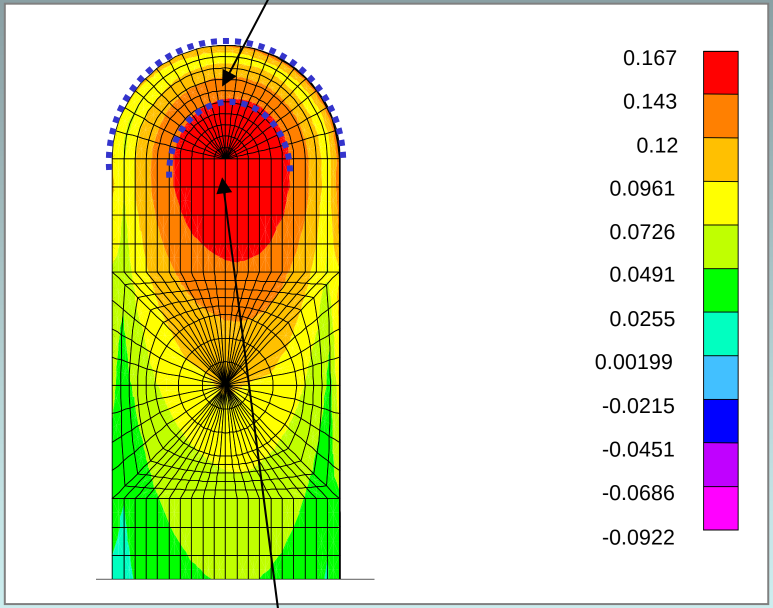


Example: Design of Solar Panel with Local Safety Concept





≈ 0,14 N/mm² < σ_D = 0,29 N/mm²



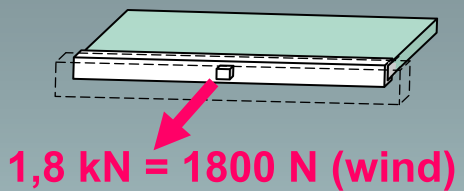
max. principal stress at load introduction

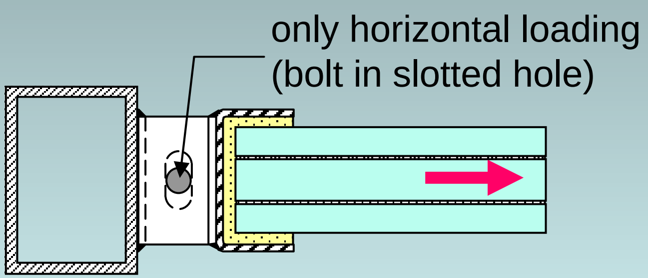
≈ 0,17 N/mm² < σ_D = 0,40 N/mm²

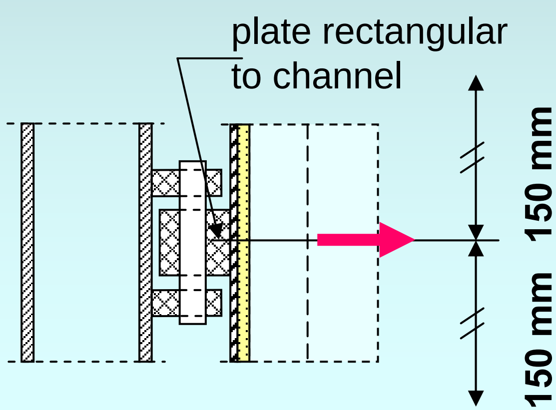
Shown in the example:
- Bonded attachment of a solar panel instead of point-fixings
- Application for simple two-sided bonding design beyond ETAG 002 - geometries

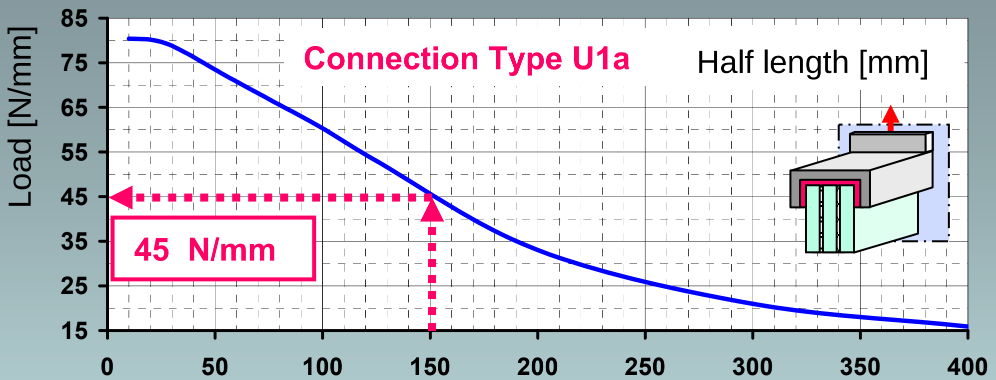
Example: U-type Bonding with Safety Concept acc. ETAG 002

Using Design Charts for Different Bonding Geometries, Based on Tests and FEA on Limit Load Level









Design load – short term loading:

P_{lim} = 2 x 150 x 45 = 13.500 N

P_{des} = 13.500 / 6 = 2.250 N

= 2,25 kN > 1,8 kN

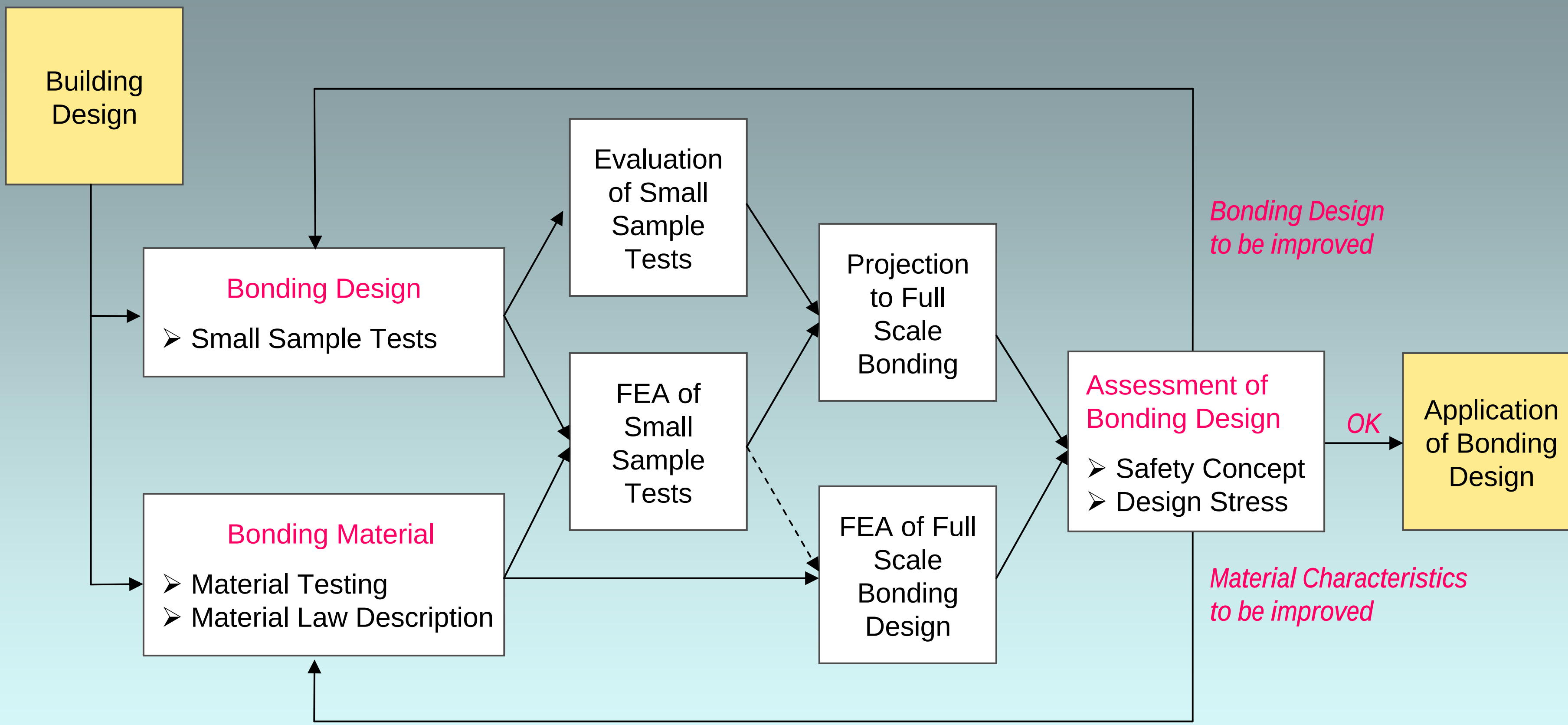
Safety factor γ = 6 (short term loading)

Shown in the example:

Application for complex U-type bonding design beyond ETAG 002 - geometries

Test and Development for Complex Bonding Designs

Flow Diagram Summarizing Design Procedure Based on Small Sample Tests and FEA



Small sample tests allow a deeper understanding of complex bonding design based on experimental results and additional FEA

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3. Conclusions and Outlook

Conclusions

- For classical structural silicone glazing, guideline ETAG 002 exists:
  - Design space of bonding is limited to simple rectangular cross-section
  - Other bonding designs not covered in existing design rules
- No base exists for testing and modelling of silicone as classical material
  - Development of global silicone material model is necessary for design of complex bonding geometries
  - Material model of silicone is highly complex due to different phenomena such as hyper-elasticity, Mullins effect and visco-elasticity.
- Characterizing of physical properties of silicone are possible by
  - Material tests – in addition with
  - Small sample tests – highlighting the impact of boundary conditions and failure mechanisms
- Finite element analysis for small sample tests helps to understand complex behavior of bondings
- Limit stress levels exist under tension loading
  - which are almost independent from application design for U-type bonding, point-wise bonding, …
  - key is suppression of lateral contraction

Outlook

- Related development and test logics are necessary for successful application of silicone bonding designs beyond ETAG 002
  - which can be used for complex bonding geometries with today's knowledge.
- Assessment of the bonding design is needed
  - based on a synthesis of material and small sample tests and finite element analyses
- Significant efforts still be recommended for:
  - a comprehensive general material model for silicone, allowing a significant reduction of tests
  - a useful safety concept based on partial factors according to EC0 (DIN EN 1990 2002) with special consideration of elastomeric material characteristics

Thank you for Attention

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