Fachverband Konstruktiver Glasbau e.V.

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Structural Silicone Sealants in Structural Glass Systems

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1. Introduction

1.1 Background

This document was prepared by Fachverband Konstruktiver Glasbau (FKG) e.V., WG Bonding. It includes technical requirements for the design of structural sealant joints in structural glass systems and refers to the principles of the European Technical Approval 002 [1], [2] (ETAG 002) as the currently applicable technical rules and regulations for structural sealant glass applications. It is anticipated that the two standards EN 13022 [3] and EN 15434 [4] will replace ETAG 002 (as of May 2021).

The technical note considers the state-of-the-art as the decisive content and extends the scope of the structural seals set out in ETAG 002.

This document is intended to give the user relevant information on the practical implementation of bonded designs in construction. Until now, bonded joints in Germany are usually governed by a project-related approval (Zustimmung im Einzelfall – ZiE) / project-related construction technique permit (vorhabenbezogene Bauartgenehmigung – vBg) or national technical approval (Allgemeine bauaufsichtliche Zulassung – AbZ) / general construction technique permit (Allgemeine Bauartgenehmigung – ABg). It is recommended to involve the responsible Supreme Building Authority in the approval procedure in good time. Even in the absence of any specifications provided by the design company, the responsible authority should be contacted at an early stage during the planning phase by the parties involved in the project. Support from an acknowledged monitoring and certification body is recommended.

DIN 2304-1 [5] describes the state-of-the-art of the quality requirements for the application details of adhesive bonds along the bonding process chain. This standard serves as the accepted basis for this document in the relevant areas. The project-specific implementation must be specified in cooperation with the sealant producer and, if necessary, the monitoring and certification body.

The sealant must be selected in cooperation with the project partners. However, there is currently a rather small choice of sealing systems with national technical approval.

The following criteria must be fulfilled to ensure safe, economic and durable bonded joints:

1. Specific material characteristics of the silicone sealant used with ETA approval
2. Calculation and design rules extending the previously applicable rules based on ETAG 002 [1], [2]
3. Quality control (high process safety) and monitoring depending on the risk classification monitoring

This technical note is intended to allow the uniform design, application and quality control of the bonded joint details of structural glass systems at national level.

This technical note is based on the author's more than 20 years of experience and knowledge in the field of bonded joints in structural glass systems. ETAG 002 [1], [2] has fundamentally proved its worth in terms of its verification concept. There are also extensive positive experiences for applications outside of the scope of ETAG 002, most of which have been included in this technical note.

1.2 Objective

The objective is to create a nationally approved document for the verification of structural sealant joints in structural glass systems, which is to be included in the European standardisation in the medium term. This technical note supplements ETAG 002 [1], [2] for SG silicone sealant joints with the boundary conditions stated in the following sections and with the following extensions:

- specification of the current state-of-the-art (beyond ETAG 002 [1], [2])
- standardisation of numerical modelling options taking account of the superposition of short term loads, wind and temperature loads, with extension for permanent loads at a later date. The design does not take account of the effect of a three sided adhesion which must be considered separately, if required (see Figure 1)
- removal of the “mechanical safeguard” requirement for installation heights greater than 8 m
- possibility of on-site bonding (new build/repair bonding) under special requirements (e.g. provision of monitoring activities)

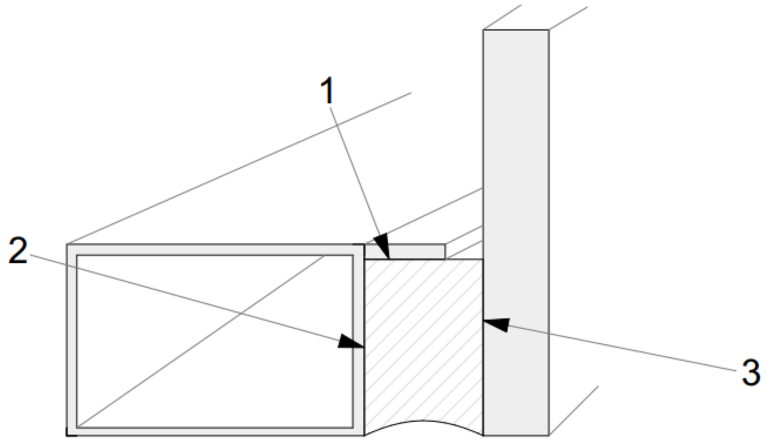


Figure 1 Example of three sided adhesion (Source: ETAG 002), ©Verrotec

1.3 Scope

ETAG 002 is a guideline prepared by the European Organisation for Technical Approvals (EOTA) specifically for Structural Sealant Glazing Systems (SSGS) and is the basis for issuing a European Technical Assessment (ETA), which in Germany is allowed to be issued by the “Deutsches Institut für Bautechnik” (DIBt).

1.3.1 Boundary conditions in accordance with ETAG 002

For the sake of completeness, the very restrictive requirements and boundary conditions set out in ETAG 002 are listed below:

- SG silicone with ETA approval, e.g. DOWSIL 993 [6], DOWSIL 895 [6], Sikasil SG-500 [7] or Ködiglaze S [8] in accordance with ETAG 002 [1], [2] (scope according to the approval for the structural bond of the IGU edge seal or in the form of an SG bond)
- adherends as per ETAG 002 (anodised aluminium, stainless steel, glass, enamelled glass, coated aluminium with verification of suitability)
- consideration of the varying impacts such as wind and temperature that cause tensile and shear stresses in the bonded joint
- rectangular glass panes
- standard SG joints as factory-applied linear adhesive silicone bead on all sides in one continuous perimeter length with a rectangular cross section (see Figure 2). Compliance with the boundary conditions listed below is recommended:
  - minimum joint thickness $e \geq 6$ mm
  - maximum joint width $h_e < 20$ mm
  - joint ratio $1 \leq h_e / e \leq 3$
- no adhesion to three surfaces; the adhesion to a spacer profile in an insulating glass unit is not considered as structural (adhesive)
- permissible inclination of SG glazing to the horizontal $\alpha > 7°$, see Figure 3
- max. deflection of support frame: L / 300 (where L: lateral length of support frame)
  max. deflection in pane centre (short side): l / 100 (where l: short lateral length of glass pane)

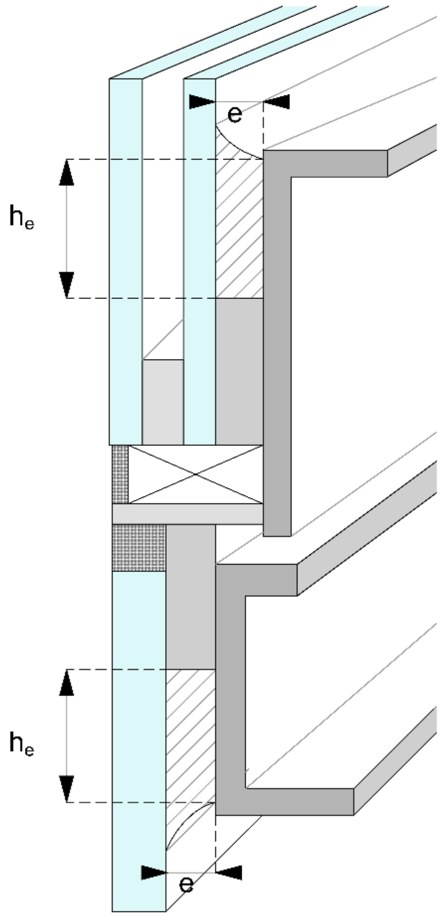


Figure 2 Indication of joint thickness e and joint width h_e [2], ©Verrotec

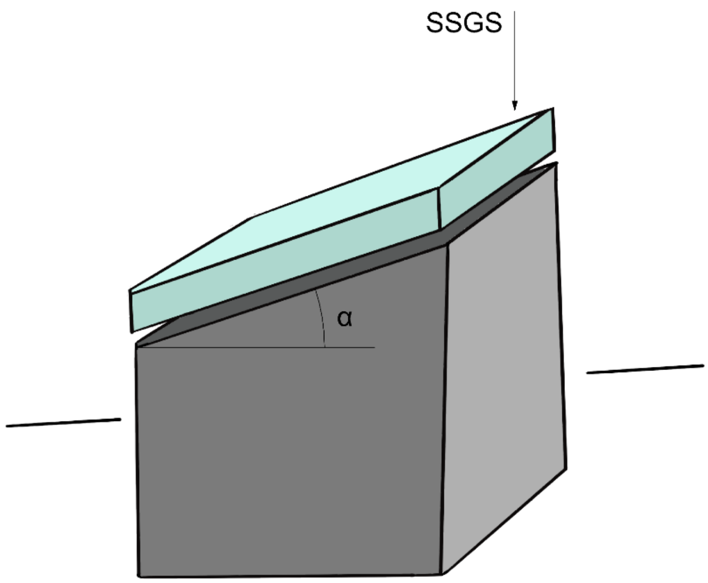


Figure 3 Permissible inclination of SG glazing in accordance with ETAG 002, ©Verrotec

1.3.2 Extended boundary conditions

This technical note includes rules for bonded joints of any pane geometries, extended bonded joint geometries and panes not bonded on all sides around the perimeter:

- no structural bond on all sides of glass panes necessary, e.g. glass panes bonded on two sides, all-glass corners
- freedom of geometry (any pane and joint geometry) (see Figure 4)

1.4 Notes on cavitation-sensitive and cavitation-insensitive bonded joints

In a simplified approach, elastic silicone sealants are incompressible. Therefore, when transverse contraction is highly constrained, in addition to cracks originating from the surface, voids or “cavities” can also form in the material, which greatly reduce the stiffness and loadbearing capacity of the bonded joint. The following approach is a simple engineering criterion to find out whether an adhesive bond exposed to tensile stress is susceptible to cavitation when using adherends of ideal stiffness.

$$S = \frac{A}{U \cdot e}$$

with
A = bonding surface [mm²]
U = perimeter of bonded joint [mm]
e = thickness of bonded joint [mm]

where S is the ratio of the extended bonding surface A related to the product determined from the perimeter U and the bonded joint thickness e (see Figure 2). For $S \leq 3$ the bonded joint is cavitation-insensitive which allows a traditional verification in accordance with ETAG 002 or with this document. If $S > 3$, verification should include the volumetric behaviour and in particular the cavitation failure of the bonded joint.

The design of cavitation-sensitive bonded joints is still part of various research projects. For more details on the verification of cavitation-sensitive bonded joints, refer to the examples given in [9]. Reference is also made to the necessary coordination with the sealant manufacturer. Figure 4 shows some illustrations of the classification of bonded joints.

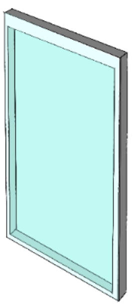
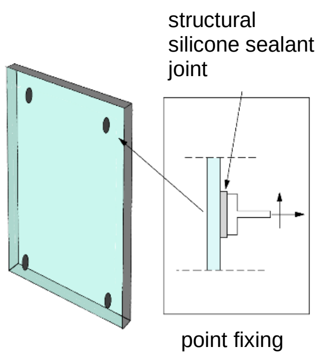
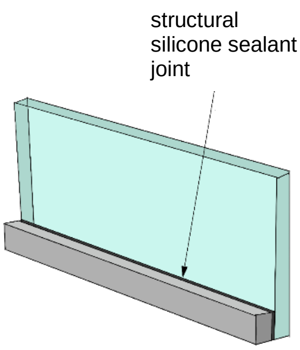
Adhesive bond in accordance with ETAG 002	**Point support**	**Bonded glass spandrel**
		
Cavitation-insensitive	**Cavitation-sensitive**	**Cavitation-insensitive or cavitation-sensitive (depending on geometry)**

Figure 4 Classification of bonded joints into cavitation-sensitive / cavitation-insensitive, ©Verrotec

1.5 Matching materials and design

The application of this guideline is subject to the following boundary conditions:

- durability of bonded joints must be ensured by designing an adhesive bond using matching materials (see e.g. [3], [4], [10]).
- prevention of unfavourable structural loads [10]
- prevention of permanent restraining forces
- prevention of multi sided adhesion by provision of a backer rod
- prevention of high peel stresses, because their linear impact causes stress peaks in the bonded joint bonding geometry. This can be remedied by re-designing the bonding geometry (see Figure 5).

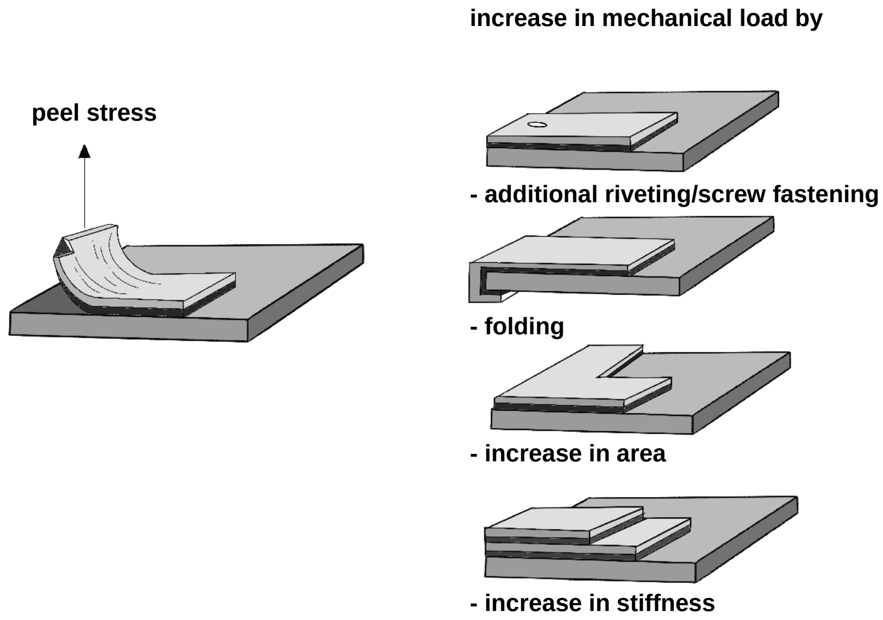


Figure 5 Design options to prevent peel stress in adhesive bonds [10], ©Verrotec

To ensure the design of adhesive bonds using suitable materials, the following aspects must also be taken into account:

- standing water on the bonded joint is not permitted
- permanent humidity of the bonded joint must be avoided
- excessive mould, moss, lichen or algal growth must be prevented or avoided
- temperatures below the dew point in the area of the bonded joint must be prevented if possible
- three sided adhesion must be avoided

In addition, curing of the sealant must be ensured in consultation with the sealant producer. This is mainly determined by the joint width, joint depth and flash-off area and the sealant system used (1-component or 2-component).

1.6 Material compatibility

Material compatibility according to this technical note refers to assuring the technical and visual functions of an entire system or assembly over the expected service life.

Material compatibility of assemblies and systems must always be ensured, because otherwise infiltration, delamination, adhesive loss and material changes are possible, which may lead to bond failure. Material compatibility refers on the one hand to the sealant and the relevant adherend, but on the other hand to the compatibility of the bond and, for laminated safety glass, to the compatibility of sealant and film.

1.6.1 Required verifications

As regards the polymer-based materials normally used in façade construction, the emphasis is predominantly on the bonding and sealing performance. For testing the relevant characteristics, success has been achieved for the test methods set out in ETAG 002 for SG sealants and those set out in RAL GZ 716 (GKFP, Bonn) [11] and VE 08, DI 01 [14], and DI 02 [15] (ift, Rosenheim) for other components. The processing guidelines must be observed.

It should be noted that the periods of validity stated in the test reports refer only to the relevant test reports and not to the documented test results. The latter depend on the constancy of the materials composition, which must be verified in cooperation with the relevant manufacturer on the basis of the documented batch numbers of the materials used for testing.

Manufacturers provide information on the compatibility of their materials when in contact with other materials, ideally with reference to the function of a specified overall system. This, however, does not include any statement on the various other (contact) materials. Information must therefore always be requested from all material suppliers involved. Materials usually in contact with SG sealant joints are laminate/composite materials, glass blocks, seals/gaskets, EPDM or silicone spacers, glazing tapes, etc.

The compatibility of sealant and interlayer must be ensured everywhere where contact between sealant and interlayer of LG/LSG is intended by design, or contact cannot be excluded.

1.6.2 Risk minimisation

Damage caused by material incompatibility can be prevented or the risk at least minimised by detailed checks and compatibility tests beforehand. Test results do not usually guarantee overall compatibility but always require interpretation within the system. Compatibly lists should therefore be viewed with caution. Apart from the compatibility tests mentioned above, the risk of incompatibility reactions can be further minimised by keeping to some basic rules.

- avoidance of direct contact
- use of low-risk materials (e.g. PP, PA, PE, APAO/POM, thermoset plastics, post-cured silicone profiles)
- use of materials with similar polarity and adjusted plasticisers

The applicable glazing guidelines must also be adhered to, such as e.g.:

- limiting the joint depth of 1C-silicones (e.g. weather sealing) to 10 mm, with compatible backing materials such as closed-cell PE-backer rods
- proper rebate ventilation
- use of high-quality film laminates without cut edges

Even when using technically perfect film laminates, bubble formation and detachment of a few millimetres due to shrinkage in the contact area cannot be entirely ruled out.

2. Calculation and design of silicone bonds

2.1 Calculation method in accordance with ETAG 002

ETAG 002 provides equations for dimensioning the joint thickness e (as a function of the temperature) and joint width h_e (as a function of the negative wind pressure). In this case, the dimensions of the bonded joint are determined on the basis of the permissible stresses of the sealant used.

The equations listed below have been successfully applied in the past and, with a global "safety factor" (correct: method factor) of 6, cover numerous uncertainties, methodological inaccuracies and local stress peaks in the material. The global safety factor 6 refers to short-time loads such as wind and temperature. Permanent loads caused, e.g. by the dead weight of the glazing, require an additional "creep factor" of at least 10, to prevent the occurrence of creep mechanisms in the sealant.

As set out in ETAG 002 [1], Annex 2, the joint dimensions can be determined as follows:

- Joint width: $h_e = \left|\frac{a\,W}{2\sigma_{des}}\right|$

  where: a = dimensions of the short side of the glass pane [mm]

  W = action of wind [MPa]

  σ_{des} = design value of tensile stress [MPa]

- Joint thickness: $e = \left|\frac{G \cdot \Delta}{\tau_{des}}\right|$

  where: Δ = the maximum thermal movement in longitudinal direction of the joint [mm]

  G = shear modulus [MPa]

  τ_{des} = design value of shear stress [MPa]

The design values for tensile and shear stresses must be regulated in the context of the product approval (ETA). The above equations can be used to determine the necessary joint dimensions directly – without superposition of tensile and shear stresses.

Table 1 gives an example of permissible stresses for the two-component materials DOWSIL 993, Sikasil SG-500 and Ködiglaze S. One-component materials with valid product approvals can also be used.

Table 1 Examples of sealant characteristic values (DOWSIL 993, Sikasil SG-500 and Ködiglaze S) according to the relevant product approval

		DOWSIL 993	**Sikasil SG-500**	**Ködiglaze S**
Manufacturer		Dow	SIKA	Kömmerling
ETA No.		ETA-01/0005	ETA-03/0038	ETA-08/0286
σ_{des}	**[MPa]**	0.14	0.14	0.14
τ_{des}	**[MPa]**	0.11	0.105	0.21
τ_{∞}	**[MPa]**	0.011	0.0105	0.0105
E-modulus	**[MPa]**	1.4	1.5	2.8
G-modulus	**[MPa]**	0.47	0.50	0.93

Note:

The E-modulus values given in Table 1 were determined on substance samples (dumbbell samples) based on DIN ISO 527-1 [14] and only apply to joint dimension calculations in accordance with ETAG 002 (see above calculation equations). Depending on the bonded joint geometry and in consultation with the sealant producer, project-related values and, if necessary, experimental tests must be used to determine the E-modulus / G-modulus.

2.2 Verification in line with ETAG 002

The equations given in Section 2.1 for the calculation of the joint width h_e and joint thickness e can be generalised as shown below. Under the conditions set out in ETAG 002, acting forces can be converted into stresses and verified. This is helpful for a variety of practical applications such as uniaxially tensioned and bonded glass panes or corner bonds.

The predominant tensile stress is determined as follows:

$$\sigma = \frac{F}{h_e}$$

where: F = force per unit length [N/mm]

h_e = joint width [mm]

Shear stress is calculated in the same way:

$$\tau = \frac{F}{h_e}$$

where: F = force per unit length [N/mm]

h_e = joint width [mm]

The associated shear (for small angles) is obtained from:

$$\tan\gamma \approx \gamma = \frac{\Delta l}{e}$$

where: γ = shear angle [rad/°]

Δl = change in length (e.g. due to temperature) [mm]

e = bond line thickness [mm]

Verification of sufficient loadbearing capacity of a bonded joint in accordance with ETAG 002 requires the evaluation of the following equations:

Verification of tensile stress: $\sigma \leq \sigma_{des}$

Verification of shear stress: $\tau \leq \tau_{des}$

The superposition of tensile and shear stresses is verified using the following interaction equation:

Interaction of tension and shear: $\sqrt{(\sigma/\sigma_{des})^2 + (\tau/\tau_{des})^2} \leq 1.0$

where: σ_{des} and τ_{des} are permissible stresses in accordance with ETA (see Table 1)

2.3 Verification using the simplified method (replacement/spring model)

Calculation methods have become established where the calculation model uses replacement springs to simulate the bonded joints. The use of spring models for calculation is a requirement for the practical application in building construction, because this allows the impact of the adhesive bond on the structural performance to be shown for global models. The calculation model must be sufficiently precise, easy to use and clear. Non-linear geometric effects due to major deformations (Theory 2nd Order) must be taken into account in individual cases.

The spring models can be used to determine the stress distribution in the bonded joint with good accuracy, taking into account the adherend stiffnesses and the global loadbearing behaviour. The calculation effort is significantly less than with 3D volume elements (see Section 2.4), but greater than with the manual calculation methods discussed in Section 2.2.

2.3.1 General concept

In this concept, a silicone joint is modelled using a series of linear force-displacement springs, where bending moments cannot be transmitted. This idealised joint can be considered to be fulfilled if the joint ratio $1 \le h_e / e \le 3$ is maintained. Due to discretisation, the stresses in the joint are averaged. The method discussed applies only to small deformations if the non-linear material behaviour can be approximated by a linear-elastic approach. The tensile or shear stiffnesses to be applied depend on the joint geometry and the resulting tensile and shear deformations. The sealant manufacturers may be able to provide relevant data on a case-by-case basis (usually by supplying an E-modulus E_{joint} and a shear modulus G_{joint}).

In the next step, the linear spring stiffnesses are calculated on the basis of the material and geometry stiffnesses (determined by experiment if necessary) based on the tensile and shear stiffnesses, E_{joint} and G_{joint}:

Spring in thickness direction: $k_N = \frac{E_{joint} \cdot A}{e}$

Spring in transverse direction: $k_V = \frac{G_{joint} \cdot A}{e}$

where: A = area = width x length (e.g. 20 ·100 [mm])

e = bond line thickness (e.g. 10 mm)

Area A relates to the selected discretisation using springs and will be explained in more detail below. If the stress verifications listed below are fulfilled, then the distortions in the silicone joint are also to be considered to be low, which justifies the assumption of linear stiffness. The spring model must be validated on the basis of experimental results:

Example: Determination of characteristic spring values for Figure 6 in the global calculation model:

Boundary conditions:

Bonded joint height (bite) e = 12 mm

Bonded joint width h_e = 20 mm

Elasticity modulus of the sealant as a function of the joint geometry: E_{joint} = 4.0 MPa

Shear modulus of the sealant as a function of the joint geometry: G_{joint} = 0.70 MPa

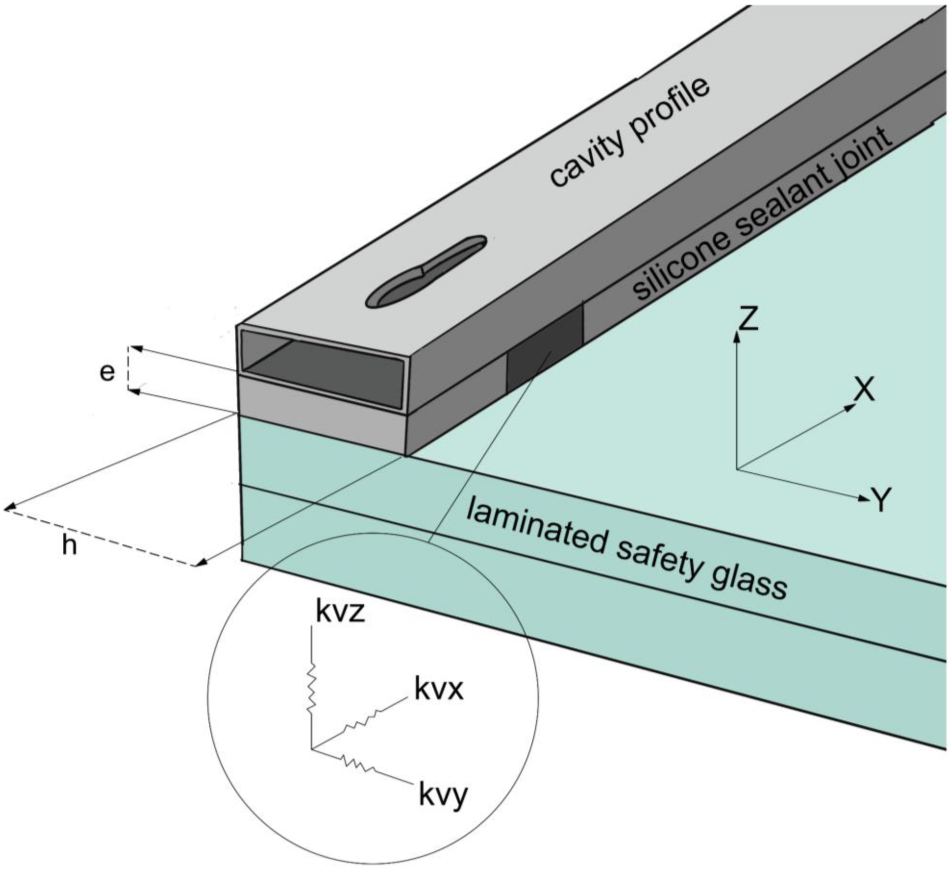


Figure 6 Spring model of a typical bonded joint, ©seele/Verrotec

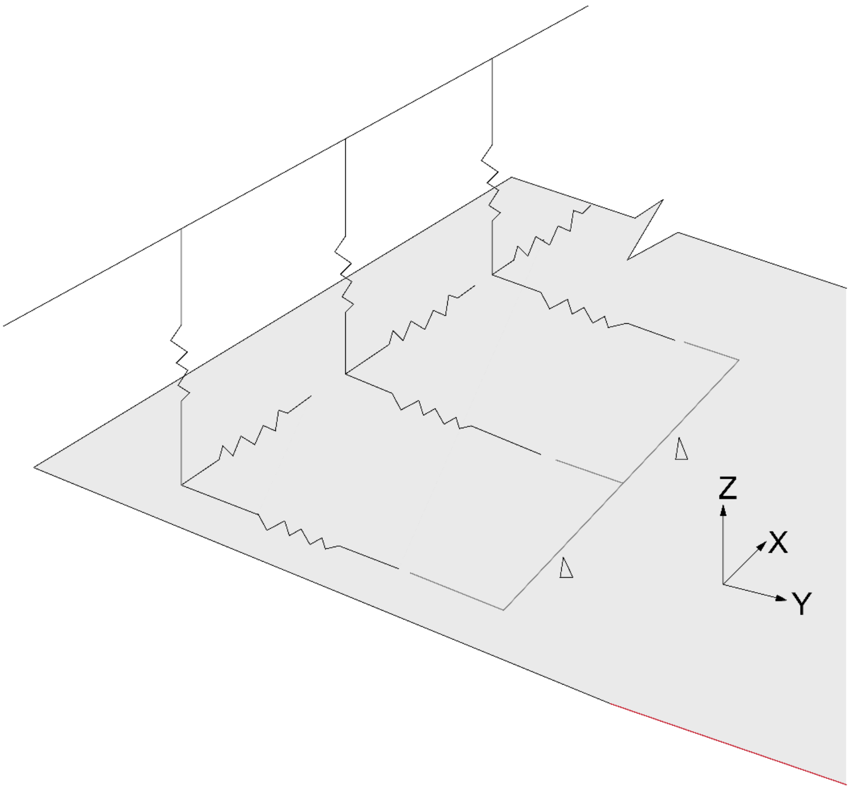


Figure 7 Diagram of the bonded joint in the design software, ©seele/Verrotec

In the example shown, the cavity profile is the beam element (see Figure 7), the pane is the shell element and the bonded joint is shown via springs with distance Δ. The distance Δ between the springs corresponds to the length for determining the bonded joint area to establish the joint stiffnesses.

$$A = \Delta \cdot h_e$$

Δ must be specified as a function of the building component, with sufficient convergence (similar to the convergence considerations for FE calculations; in practice a discretisation between 50 and 100 mm has proven successful). If loads or stresses concentrate in specific model areas, it is recommended to refine the discretisation of the bonded joint in these areas. The spring stiffnesses k_N and k_V must be adjusted to the particular discretisation.

Each spring must be assigned the relevant direction-dependent bonded joint stiffnesses (here with A = 100 x 20 = 2,000 mm²):

$$k_N = \frac{E_{joint} \cdot A}{e} = \frac{4\ MPa \cdot 2000\ mm^2}{12mm} = 666.7\ N/mm$$

$$k_V = \frac{G_{joint} \cdot A}{e} = \frac{0{,}7\ MPa \cdot 2000\ mm^2}{12mm} = 116.7\ N/mm$$

Spring stiffness k_V can be applied both to longitudinal and transverse joint directions and is indicated by k_{Vx} and k_{Vy} in Figure 6.

The next step is to enter the determined joint stiffnesses into the design software or the global design model. The simplified model is used to calculate the impact and stiffness-dependent internal spring forces.

The combination of actions in the ultimate loadbearing state as per EN 1990 gives the factorised internal spring forces. For the ETAG 002-compliant case, the internal forces must be determined using characteristic loads.

Actions or forces in the springs (design values):

Tensile force in the spring:	+N	
Compression force in the spring:	-N	(usually not verified)
Resulting transversal force in the spring:	$V = \sqrt{V_x^2 + V_y^2}$	

The resulting forces in the springs must then be divided by the sealant surface to obtain the corresponding stress value (as in Section 2.2).

Resistances (design values):

To determine the design resistance as closely as possible to the object-related bonded joint geometry experimentally, a characteristic design value σ_{ult} must first be determined for the bonded joint geometries similar to the components. For example, the fracture strengths of the bonded joint geometries can be statistically evaluated in accordance with ETAG 002 and the 5% quantile strength value determined. The characteristic fracture strength determined in this way must then be divided by the method factor γ to account for uncertainties from the calculation model, the ageing behaviour of the sealant and uncertainties in the description of the action side. For the method factor γ, a value of 4 (up to 6) can be applied after consultation with the sealant manufacturer and the responsible building supervisory authority if a more precise calculation method is used.

The experimentally determined permissible stress of object-related bonded joint geometries is given by:

permissible tensile stress: $\sigma_{\mathrm{des}}^{\mathrm{Exp}} = \frac{\sigma_{\mathrm{ult}}}{\gamma}$

permissible shear stress: $\tau_{\mathrm{des}}^{\mathrm{Exp}} = \frac{\tau_{\mathrm{ult}}}{\gamma}$

where σ_{ult} or τ_{ult} are the 5% fractiles of the breaking strength obtained by experiment.

In many cases, the object-related ultimate strengths σ_{ult} and τ_{ult} can alternatively be determined from the permissible stresses specified in the ETA by multiplying the permissible stress by the method factor γ = 6. For the sealants listed in Table 1, the permissible tensile stress is e.g. σ_{des} = 0.14 N/mm², so that σ_{ult} is given by: σ_{ult} = 6 x σ_{des} = 0.84 N/mm².

If approved by the sealant manufacturer the following applies: σ_{des}^{Exp} = 0.84 / 4 = 0.21 N/mm² for γ = 4.

<u>Verification of variable actions:</u>

Verification of tensile stresses: $\sigma / \sigma_{\mathrm{des}}^{\mathrm{Exp}} \leq 1$

Verification of shear stresses: $\tau / \tau_{\mathrm{des}}^{\mathrm{Exp}} \leq 1$

Interaction of tension and shear: $\sqrt{\left(\sigma / \sigma_{\mathrm{des}}^{\mathrm{Exp}}\right)^2 + \left(\tau / \tau_{\mathrm{des}}^{\mathrm{Exp}}\right)^2} \leq 1$

2.3.2 Experimental determination of stiffnesses

Sealant manufacturers are usually able to provide the stiffness values E_{joint} and G_{joint} for ETA-compliant bonded joints. If the planned bonded joint geometries deviate from the limit dimensions defined in ETAG 002 or do not correspond to the joint geometries given in the corresponding sealant approvals, component tests must be conducted with the project-specific bonded joint geometries. In the absence of values provided by the manufacturers in the relevant approvals for the stiffnesses of the sealant as a function of the bonded joint cross section, the sealant stiffnesses E_{joint} and G_{joint} must be determined by testing. The tests can be used at the same time as the determination of the stiffnesses σ_{ult} and τ_{ult}. The test setup and scope must be agreed by the parties involved and the sealant manufacturers on a case-by-case basis. A project-specific bonded joint geometry of adequate length must be tested. To minimise edge effects, the joint length l of the test specimens should be three to five times the width h_e of the bonded joint.

Experimental determination of tensile and shear stiffnesses

The tensile elasticity modulus E_{joint} is determined by exposing the project-specific modified H-samples to the permissible stress σ_{des}. The tensile force used to determine the tensile elasticity modulus on the ETAG H-sample is given as follows:

$$F_{\mathrm{des}} = h_e \cdot l \cdot \sigma_{des}$$

using σ_{des} according to ETA (see Table 1), l = joint length

The shear force to determine the shear stiffness of the ETAG H-sample in the longitudinal or transverse direction of the joint is determined in the same way as follows:

$$V_{\mathrm{des}} = h_e \cdot l \cdot \tau_{des}$$

using τ_{des} according to ETA (see Table 1), l = joint length

Project-specific adjustments of F_{des} or V_{des} may become necessary if the tensile level deviates significantly from the permissible stresses used. The loading speed for the test is 5 mm/min in accordance with ETAG 002.

Scope of testing

Due to the statistical significance of the test results, at least five samples per parameter must be tested and statistically evaluated.

Determination of the geometry-dependent elasticity modulus and shear modulus

The tensile-stress strain diagrams or shear-stress strain diagrams can be used to determine the bonded joint geometry-dependent elasticity modulus and shear modulus (secant modulus):

$$E_{joint} = \frac{\sigma}{\varepsilon}$$

$$G_{joint} = \frac{\tau}{\gamma}$$

where: ε = strain [mm/mm]

γ = shear angle [rad/°]

2.4 Verification using 3D volume elements in accordance with the Finite Element Method (FEM)

2.4.1 General concept

The verification of the bonded joint by FE calculations can be suitable particularly for special object-related solutions. This section provides assistance for the verification of bonded joints using 3D volume elements. Due to the complexity of this type of verification it should be applied only with sufficient FEM knowledge. In most cases verification is sufficiently accurate using the manual calculation methods (Section 2.2) or spring models (Section 2.3).

The necessary steps for the experimental and numerical characterisation of a sealant are described in what follows. However, it should be noted here that the sealants commonly used in building practice (see Section 2.1), have already been experimentally characterised, and there are validated material models, so that these sealants do not require steps 1-3.

1. Experimental database of the sealant in the form of technical stress-strain relationships for uniaxial tension, simple shear, or biaxial tension under quasi-static boundary conditions. In the case of a three sided adhesion or non-compliance with the joint ratio specified by ETAG 002, additional top tensile tests (cross tension tests) are required to analyse the compressive behaviour of the sealant under hydrostatic stress states (see Figure 8).

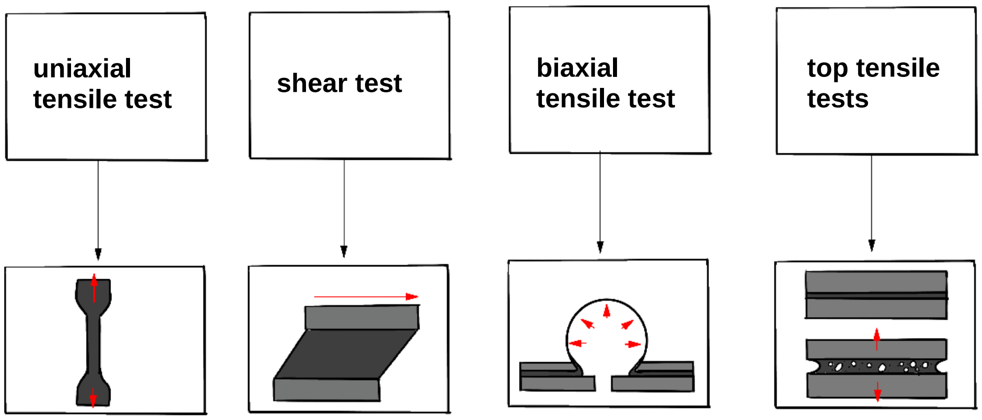


Figure 8 Diagram of tests required for complete sealant characterisation, ©Verrotec

2. Selection of a suitable material law (e.g. neo-Hookean, Mooney-Rivlin2, Ogden, Extended Tube Model). Here the requirement is for one experiment per material parameter. If only uniaxial tensile test data are available, it is recommended to use the neo-Hookean material model. For practical applications in building construction, the assumption of a linear-elastic material law is considered to be sufficiently accurate, see Section 2.3.
3. Determination of material parameters on the basis of experimental results (uniaxial tension, uniaxial compression, simple shear) using regression analysis. Here it must be ensured that the material parameters are determined simultaneously for all the above test results.
4. Validation of the determined material parameters via recalculation of small component tests, which correspond to the actual dimensions of the bonded joint in the construction project. Testing is conducted in compliance with Section 2.3.2.

If the results of steps 1-4 are available, the safety concept set out in ETAG 002 must now be reconciled with the verification method using FE simulations. This step is necessary because FE solutions generally result in mesh-dependent solutions and the verification concept must take this into account. The necessary steps are therefore briefly illustrated below by an example:

1. Determination of mesh density for the global structural model of the construction to be verified (e.g. 2 x 2 x 2 [mm]) and simultaneous transfer of this mesh to the ETAG H-sample (see Figure 9).

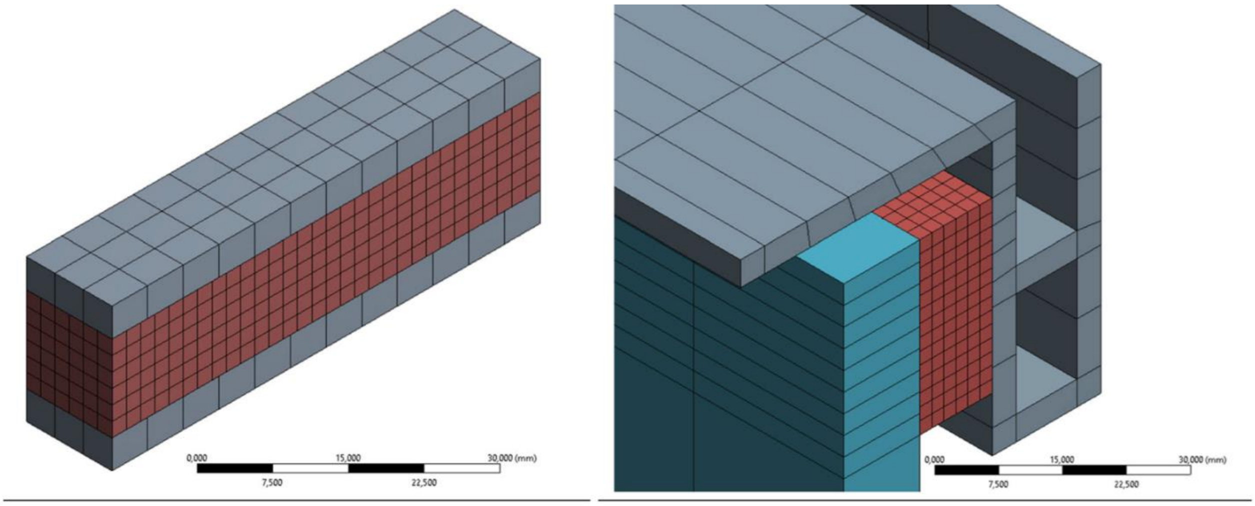


Figure 9 Identical meshing of the adhesive bond for the ETAG H-sample (left) and the bonded construction from the global model (right) [15]

2. FE simulation of the ETAG H-sample with identical mesh from the global model and load on ETAG H-sample using σ_{des} or F_{des}. Evaluation of true stresses or strains in the ETAG H-sample. Here it should be noted that this is a permissible design value which includes the effect of stress singularities. The following shows the example of a permissible true design stress g $\sigma_{1,\mathrm{des}}^{\mathrm{FE}}$ for two different meshes. The ETAG H-sample was subjected to the tensile design force:

$$F_{des} = \sigma_{des} \cdot A \ = \ 0.14 \ \mathrm{MPa} \cdot 12 \ \mathrm{mm} \cdot 50 \ \mathrm{mm} = 84 \ N$$

As shown in Figure 10, the permissible mesh-density-compliant limit stress $\sigma_{1,\mathrm{des}}^{\mathrm{FE}}$ differs considerably depending on the FE mesh selected.

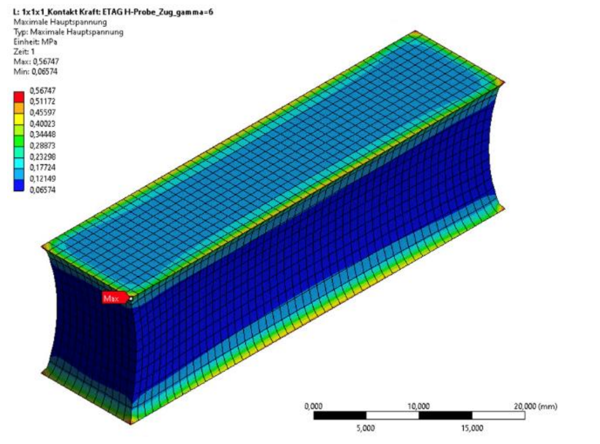
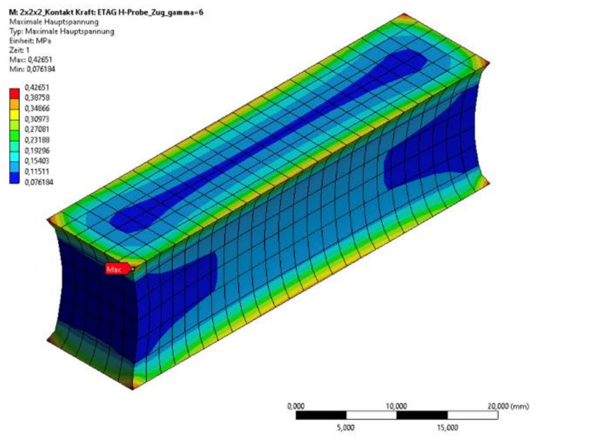
<table>
<tr><th>Mesh 1x1x1 [mm]</th><th>Mesh 2x2x2 [mm]</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>$\sigma_{1,des}^{FE}$ = 0.567 MPa</td><td>$\sigma_{1,des}^{FE}$ =0.426 MPa</td></tr>
</table>

Figure 10 Evaluation of the main tensile stress using the example of the ETAG H-sample for two different mesh sizes to illustrate the effect of stress singularities (fictitious values).

3. Calculation of the overall structural model with the exact mesh density from 1. and evaluation of the true stresses or strains in comparison with the permissible design value from 2. The selected example is based on the method factor $\gamma = 6$, which was applied to the Finite Element Method. Verification of the bonded joint using FEM is obtained as follows:

$$\sigma_{1,\mathrm{des}} \leq \sigma_{1,\mathrm{des}}^{\mathrm{FE}}$$

The meshing of the ETAG H-sample and of the adhesive bond of the global model must be identical, otherwise the verification is not permissible.

2.4.2 Experimental determination of stiffness

The experimental determination of stiffness is carried out/obtained as in Section 2.3.2.

3. Quality requirements for the bonding process

The general suitability of a bonding site and the confirmation of the compliance of the bond with the technical requirements must always be verified by a recognised certification body in the form of an **initial test.**

The production of structurally adhesive bonds must be monitored to ensure sufficient and reproducible quality during the application. This is done by the establishment of **factory production control** (FPC) and supplementary **third-party monitoring.**

The monitoring requirements are based on ETAG 002 and the state-of-the-art provided by successfully implemented projects. In addition, DIN 2304-1 [5] sets out the requirements for the quality of load-transmitting adhesive bonds along the bonding process chain – from development through production to maintenance. For structural glass systems, this content can be of assistance in mastering the bonding process and should be considered where appropriate.

Note: For structural glass systems, ETAG 002 is the current technical basis for SG structures.

DIN 2304-1 and the currently available specifications from the DIN SPEC 2305 series are not mandatory for structural glass systems. They can be seen as supporting tools for the user and can be taken into account within reasonable limits. This includes information on the classification of safety-related adhesive bonds, on a manufacturing environment suitable for bonding, and personnel qualification in adhesive bonding technology. Information is also provided on the preparation of work instructions for bonding technology.

The quality of the adhesive bond application is controlled at the production site where the adhesive bond is applied (“bonding site”, bonding company) by

- factory production control and
- regular third-party monitoring by an accredited national monitoring body.

3.1 Production monitoring

3.1.1 Requirements for the bonding company

- **Manufacturing environment in a bonding company [5]**

For quality-assured bonding operations, production areas must be available which are suitable for the bonding systems in terms of technology, occupational health and safety and environmental protection. This includes in particular ensuring the necessary environmental conditions such as temperature, air humidity, lighting, cleanliness, access restriction, avoidance of substances that interfere with adhesion/wetting, air contaminants and draughts.

Storage facilities must be available for adherends, adhesives/sealants and adhesive/sealant auxiliaries, which allow storage in compliance with the requirements.

Dangerous substances (e.g. primers) must be kept in storage facilities which comply with the applicable requirements.

The bonding areas must be specified.

- **Personnel qualification**

The bonding company must provide a sufficient number of trained personnel for the planning/design, implementation and monitoring of the adhesive bonding technology (overall bonding process) in accordance with the relevant requirements.

The bonding company must have personnel who can instruct the bonding technicians in the relevant activities and monitor and inspect the bonding details. It must have qualified and trained personnel who can create the specified adhesive bonds independently and professionally in accordance with the relevant work instructions.

DIN SPEC 2305-3 [16] details the personnel requirements for adhesive bonds of safety classes S1 to S3 in accordance with DIN 2304-1 [5] and explains the relevant professional qualifications as well as the tasks of the personnel.

In this document, bonding companies for structural glazing systems will find valuable information on the contents of training and further education in adhesive bonding technology for the personnel responsible for instruction and application. Appropriate qualifications to improve bonding results include a certificate of competence, employee qualification (according to [16]) and regular employee training or instruction.

It is recommended that bonding companies operating in structural glass construction provide adequate personnel qualification.

- **Work instructions in accordance with DIN 2304-1 [5]**

Work instructions ensure a smooth and consistent production workflow and are crucial for product quality. A detailed description of the technical bonding work processes is therefore necessary. Sealant manufacturers offer support for the preparation, providing detailed documents for their products.

The following description of the manufacturing documents is to be understood as a list of the many possible options and is neither complete nor does it have to appear in this form. The list is primarily intended to facilitate the preparation of manufacturing documents.

Work instructions are based on the following documents:

- standards, guidelines, guidance sheets
- bonding technology planning/design documents (drawings, parts lists, verifications, bonding plan)
- product-specific information (e.g. technical data sheets, safety data sheets, additional product information)
- industry-specific information

The work instructions should include the following:

- state of revision, date
- adhesives, sealants and auxiliaries (material and delivery form)
- special tools and devices
- operational requirements (e.g. personnel qualifications, environmental conditions such as temperature, humidity and light)
- detailed process description for, e.g.:
  - inspection of sealants/adhesives and auxiliaries (identity, required quantity(s), shelf life, shelf life of open containers, container damage, obvious colour/consistency deviations)
  - inspection of adherends (identity, damage/defects), dimensional accuracy, condition of adherend surfaces, quantities required)
  - conditioning of adherends, sealants/ adhesives, primers and other operating materials at a suitable location under suitable ambient conditions
  - cleaning (cleaning agents, cleaning aids, flash-off times, bath monitoring, recontamination prevention)
  - surface pretreatment (process description and parameters, verification of the effect if necessary, measures to avoid recontamination, determination of the min./max. time interval until bonding)

- sealant/adhesive preparation (dosage, mixing ratio, mixing tolerances, degree of mixing)
- sealant application (auxiliaries, quantity, application type, wetting, visualisation)
- joining (bond line thicknesses, bond line widths, contact pressure, wetting)
- fixing (devices, pressures, duration)
- curing (duration, temperature, additional specific parameters)

The following data are also recommended:

- information on quality assurance, process control
- troubleshooting
- specification of manufacturing documentation (traceability)
- occupational health and safety and environmental protection, disposal

3.1.2 Factory production control (FPC)

The “bonding site” / bonding company shall establish a factory production control (FPC) system, as specified by the responsible monitoring body.

A project folder with the following content must be prepared for each project order (a project-specific agreement on the concrete content must always be project-specific):

- project-specific data on quantity, dimensions, structural configurations, illustration of the bond
- project-specific information by the sealant manufacturer on applying cleaning agents and primers to the surfaces used
- all mandatory “type 2.2” test reports in accordance with DIN EN 10204 [17] for the surface treatment of metallic profiles
- all project-specific product verifications for the glass building components to be used
- daily work reports on factory production control
- results of adhesion tests and failure patterns of type A samples
- results of tensile strength tests and failure patterns of type B samples
- results of extra samples prepared per project provided by the monitoring body in accordance with the surveillance contract
- special features during production
- positioning of each individual SG unit or of SG unit batches in the building project

All test results must be entered in the factory production control report. The sealant manufacturers’ guidelines must be followed.

Sealant tests on each working day

The following tests must be carried out on the sealant on each working day:

1. 1-component systems: skin-over time / elastomer test
2. 2-component systems: checking homogeneity (no streaks) of the sealant mixture using the "Butterfly Test". If the evaluation is unclear, the tests must be repeated with two glass plates.
3. 2-component systems: checking snap time or mixing ratio
4. Shore A hardness is measured on the adhesion test sample after a 24 h curing time (2-C systems) using a shore-hardness durometer with slave pointer. The minimum value specified by the sealant manufacturer must be reached after 24 hours. The curing time of 1-C systems is usually longer (observe manufacturers' instructions).

Adhesion tests of type A samples on each working day based on ETAG 002 (peel test)

The adhesion tests of type A samples are specified in the relevant ETA approvals and the sealant manufacturer guidelines. They serve to evaluate the adhesion of the sealant to the glass and aluminium or stainless steel substrates during factory production control.

Preparation of test specimens:

On each production day, 1-3 specimens are prepared on glass and 1-3 specimens on a metallic substrate (as specified by the approval or authorisation documents): e.g. at the start of production, during production and at the end of production. Additional samples must be prepared at each batch change and after any longer interruptions to work.

The peel samples must be prepared using series-equivalent material or material in accordance with the construction details.

The surfaces to be tested are pretreated as set out in the ETA or in the manufacturer certificates covering suitable pretreatment. A bond breaker is applied at a distance of 200 mm to delimit the test area. The sealant is applied in the form of a bead of approx. 6 mm height, 25 mm width and 250 mm length (see Figure 11). At least one bead must be applied. Curing must comply with the conditions set out for the sealant in accordance with the process conditions of the original parts. The test is conducted after a curing time to be agreed with the manufacturer, usually 72 hours. For adhesion testing the bead is gripped in the non-adhesive area and manually peeled back at a 180° angle. The peeling force must be increased until a crack propagates. If the crack propagates in the sealant, new incisions must be continuously applied to the bead during the peeling process. These incisions must be continued at an acute angle between bead and adherend surface until reaching the bonding area. Between each incision there should be a time period of about 3 seconds during which the material is exposed to continued strain.

Evaluation is based on the failure patterns of the peeled beads. The failure patterns must be evaluated in accordance with ISO 10365. As a crack is also likely to propagate in coatings or at the boundary areas of a multilayer configuration of an adherend (coating material, primer, etc.), this must also be distinguished in the evaluation. The specimen has passed the test if a 100% cohesive failure occurs in the sealant. Failure within the primer layer or other coatings as well as adhesive failure are not acceptable (see Figure 12).

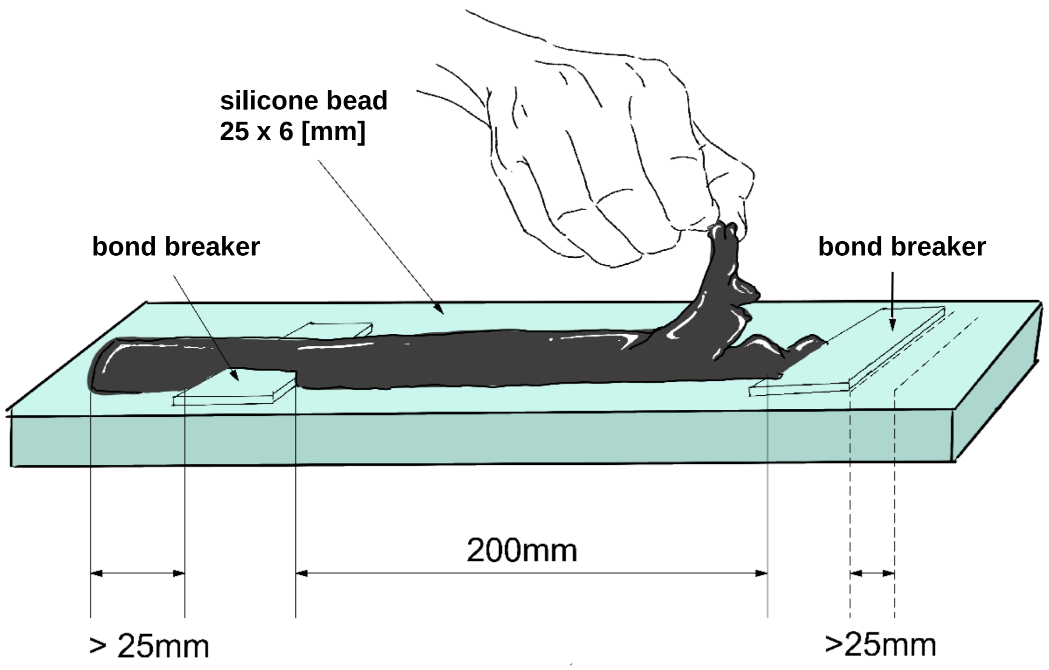


Figure 11 Peel test (Type A): Example of cohesive failure in sealant (positive evaluation) [1], ©Verrotec

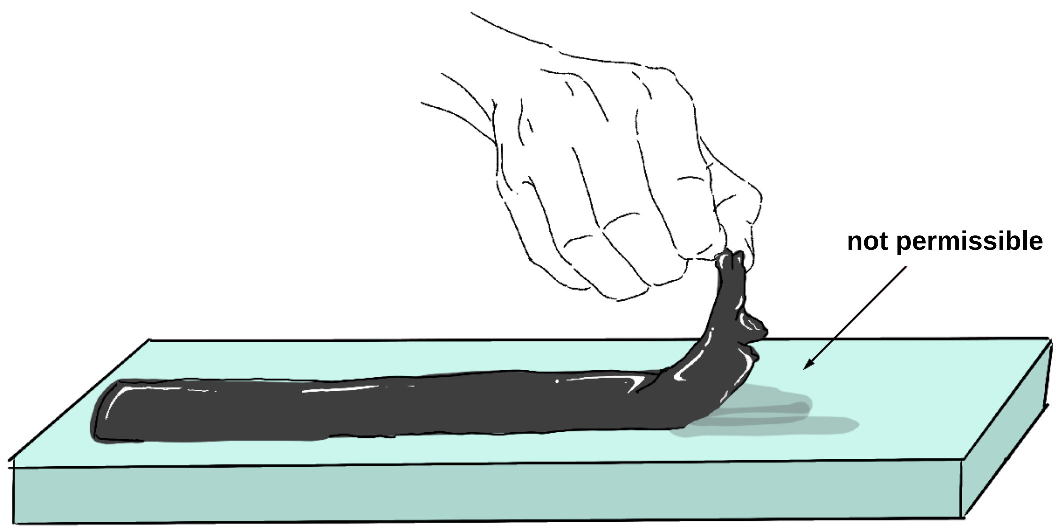


Figure 12 Peel test (Type A): Example of adhesive failure of sealant from substrate (negative evaluation) [1], ©Verrotec

As agreed with the approval holder or permit holder, when placing the order, the "planning" or "bonding company" must (depending on the subject of the contract) request short pieces of specified length of the original profile with the specified surface treatment and in the appropriate number of pieces from the metal constructor for the preparation of type A samples.

The same applies to glass. In the case of coated glass without edge stripping in the bonded area (e.g. solar control glass or enamelled glass), the identical product must be used as a substrate.

Preparation of Type B tensile test samples based on ETAG 002 (H-sample)

Figure 13 shows an example of the geometry of a type B sample. The specimens must be prepared under the same conditions as for the production of the original parts. The specimen geometries must be agreed with the monitoring bodies and may differ from the specimens shown here.

Preparation of test specimens:

Three H-samples are prepared on each production day: for example at the start of production, during production and at the end of production. Additional samples must be prepared at each batch change and after any longer interruptions to work.

The specimen quality determines the result. A suitable joining device must therefore be used for specimen preparation to achieve a defined bonding surface. The sealant is applied to the surfaces pretreated according to ETA and the specimens are joined. Curing must comply with the conditions set out for the sealant and the process conditions of the original parts. The specimens must be carefully removed from the joining devices after a minimum of 1 and a maximum of 3 days and stored until testing in accordance with the above conditions. The sealant manufacturers provide comprehensive support for this.

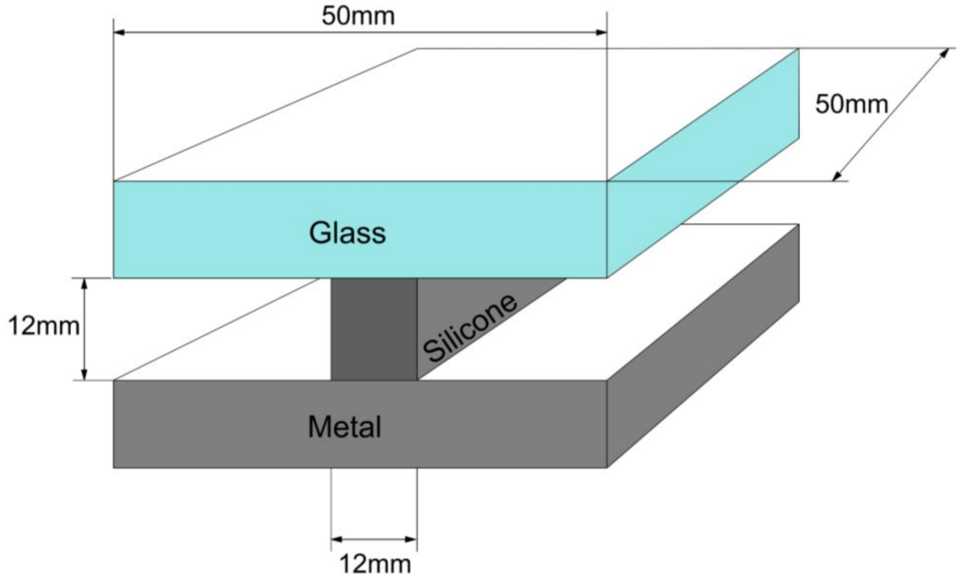


Figure 13 Example of a Type B sample, bonded joint dimensions h x e x l = 12 x 12 x 50 [mm], ©Verrotec

The "planning" or "bonding company" may (depending on the subject of the contract) request short pieces of specified length made of the same material and with the same surface treatment as specified in the project from the metal constructor for the preparation of type B samples. Alternatively, the H-samples can be prepared using non-series-equivalent glass or metal (reason: series material is not mandatory, since it is the cohesive strength of the sealant that is being tested and not the adhesive strength).

For testing, the test specimen is mounted in a suitable test device and subjected to tensile load until failure. The tensile force N applied must be measured and documented. The result must correspond to at least the minimum tensile force specified by the sealant manufacturer. The failure pattern must be evaluated in accordance with ISO 10365 [18]. As a crack is also likely to propagate in coatings or at the boundary areas of a multilayer configuration of an adherend (coating material, primer, etc.), this must also be distinguished in the evaluation. The specimen has passed the test if more than 90 % cohesive failure (CF) occurs in the sealant and less than 10 % adhesive failure (AF) in the form of detachment of the sealant from the contact area.

Table 2 Overview of the required type A and type B samples and recommendations for actions based on test results

Sample type	**A**	**B**
Frequency of sample preparation depending on approval / authorisation documents	One to three times per day, at least two different times 1 bead on substrate 1 1 bead on substrate 2 i.e. 2 - 6 specimens per day as a rule	Preferably at least two different times per day 3 H-samples i.e. at least 3 specimens per day as a rule
Preparation of specimens at the following times	• Beginning of shift / production • End of shift / production • New batch (mandatory) • Longer production interruptions (mandatory)	
Criteria for passing the test in deviation from ETAG 002	100% cohesive failure in sealant	Tensile force to rupture > minimum force as specified by sealant producer at least 90% cohesive failure in sealant
Procedure when failing the test	Troubleshooting*, logging and initiation of action	Troubleshooting*, logging and initiation of action
Procedure for unclear result when troubleshooting or errors found affecting the production	• Production stop • Inspection of the complete production process • Deglazing the affected units	

*Troubleshooting covers the entire bonding process, e.g. plant/equipment technology, mixing process if required, environmental conditions, cleaning and pretreatment processes, sealant application, etc.

Possible reasons for a failed test may include (but are not limited to):

- production rooms unsuitable for bonding work (temperature, humidity, etc.)
- surface contamination from greases, oils or solid substances (dust)
- moisture condensation due to temperature differences
- residues of protective papers or films
- inhomogeneous sealant mixture, incorrect mixing ratio of the two components or incorrect curing agent concentration
- use of reactive sealants that have exceeded the snap time
- test specimens stripped too late

Checking for cavities

The bonded joints of all SG units must be visually inspected for freedom of cavities or bubbles and the results documented. This visual inspection can be carried out directly during the installation of the bonded joint: any discontinuities must be reworked immediately.

Archiving specimens for quality assurance purposes

It is recommended to store the type A and type B samples during the warranty period of the façade or structurally sealed glazed façade units in a way that can be traced. The archiving period should be at least 5 years.

3.1.3 Third-party monitoring

The technical documents of the relevant construction products and techniques (e.g. ETA, AbZ [national technical approval] AbG [general construction technique permit]) contain requirements for factory production control and third-party monitoring. A selection of the usual requirements is detailed below. Please note that the requirements of the relevant technical documents for the products and construction techniques are binding and may deviate from the summary given below.

During the **initial test/inspection**, the monitoring/certification body verifies that the technical and personnel requirements for the proper production of SG units in accordance with the specifications of the approval/permit/requirements of the sealant manufacturer are in place and that the product meets the technical requirements.

The inspection of the factory production control is carried out by a monitoring and inspection body recognised by the national building authorities and includes the following:

- checking the factory production control (FPC) incl. documentation
- checking the production conditions for the installation of the bonded joints
- checking the measuring instruments
- monitoring the application (details)
- monitoring the testing of type A samples (adhesive test) and type B samples (tensile test) during factory production control
- sampling and testing of type A samples (adhesive test) and type B samples (tensile test) by third-party monitoring body.

  In addition to the product tests during FPC, type A and type B samples are tested by the monitoring body.

  The third-party monitoring body takes random samples from the test specimens manufactured during production that are listed in Table 2. The number of specimens for third-party monitoring must be determined by the responsible monitoring body.

The verification of the remedy of any non-conformities must be agreed with the monitoring body in each individual case.

3.2 Installation monitoring

In individual cases, installation must be monitored by a third-party monitoring body with the following objectives:

- avoiding unplanned restraints
- compliance with design requirements

The time sequence of the monitoring activities is specified by the third-party monitoring body for the relevant project. This must take place at least at the beginning of the installation work and must be implemented for each system.

The monitoring activities must be documented.

4. Monitoring and maintenance

Inspections of the installed bonded joints are intended to detect changes to the structural bond in good time and initiate appropriate action. For this purpose the bonded joints are grouped into safety classes on the basis of DIN 2304-1 [5].

Table 3 Safety classes based on DIN 2304-1 [5]

Classes of consequence	**Safety requirement**	**Examples**
S1	High	The failure of the adhesive bond ▪ leads directly or indirectly to an inevitable danger to life and limb ▪ leads to a failure of the functionality, whose effects will most likely lead to an inevitable danger to life and limb
S2	Medium	The failure of the adhesive bond ▪ may be a danger to life and limb ▪ leads to a failure of the functionality, whose effects will probably involve personal injury or result in a major environmental damage ▪ leads to a failure of the functionality, whose effects will most likely involve major damage to property
S3	Low	The failure of the adhesive bond ▪ leads to a failure of the functionality, whose effects will probably not involve personal injury or result in major environmental damage ▪ leads to a failure of the functionality, whose effects will affect comfort and performance at most ▪ leads to a failure of the functionality, whose effects will probably not involve major damage to property
S4	None	The failure of the adhesive bond ▪ leads to a failure of the functionality, whose effects will not, under foreseeable circumstances, involve personal injury or result in environmental damage ▪ leads to a failure of the functionality, whose effects will only affect comfort and performance ▪ leads to a failure of the functionality, whose effects will not involve major damage to property

Experience shows that the durability of bonded joints can usually be predicted in the first two years after manufacture. This is due to the fact that, as a rule, the lack of durability properties is caused by faulty production, and this can be detected at an early stage by careful monitoring activities.

Depending on the safety class, bonded joints must be inspected over the entire service life and at the frequency specified in Table 4, if necessary by consulting an external monitoring body. Due to warranty claims, some manufacturers carry out in-house monitoring activities, so that third-party monitoring may only be necessary as a supplement (e.g. as a check or after the warranty period) or may not be necessary at all.

Table 4 Suggestions for third-party monitoring frequency according to the safety classes

Classes of consequence	**Monitoring frequency**	**Third-party monitoring required?**
S1	frequently (at the beginning once a year, then gradually less frequently)	Yes, in agreement with authority and monitoring body
S2	periodically (at the beginning once a year, then gradually less frequently)	Yes, in agreement with authority and monitoring body
S3 / S4	none	No

The responsibility for carrying out the monitoring activities must be contractually regulated (usually the building owner or operating company). The proper performance of the inspection can be regulated by maintenance contracts.

The bonded joint can be monitored by in-process visual inspections or non-destructive test methods.

Visual inspection of bonded joints

- Detection of delaminations using suitable light sources
- Visual inspection of the bonded joints and pane cavity of the IGU; water penetration or condensate formation may indicate leaks and ageing of the edge seal or the adhesive bond

Non-destructive test methods to determine mechanical values

- Installation of sensors or displacement transducers at suitable locations and computer-aided readout, followed by evaluation

5. Cleaning

For avoiding damage to the bonded joints due to cleaning measures, neutral cleaners or cleaning agents with a maximum surfactant concentration of 1-2% (pH value approx. 7) should be used for all areas with adjacent SG joints, in agreement with the sealant manufacturer. Surfactants must be removed with water following the cleaning measures. Moisture accumulation must be avoided.

6. Literature

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