COMPENDIUM

ELASTIC BONDING

Principles and guidelines for elastic adhesive technology in industry

BUILDING TRUST

FOREWORD

HYBRID DESIGN CONCEPTS HAVE BEEN SUCCESSFULLY INTRODUCED to the transportation industry, meaning that the optimal mix of materials may be chosen for each component.

The joining of different materials in hybrid design requires new joining techniques because classic approaches such as bolting and welding simply do not meet the requirements. For this reason, thick elastic adhesives have been adopted as the technology of choice for modern hybrid designs. Elastic adhesives present a number of benefits, such as their ability to compensate for materials with different thermal elongation coefficients. With a recommended thickness range from 3 mm to 25 mm it also becomes easy to accommodate production tolerances, create a water and pressure tight finished joint and help isolate vibration. In contrast to bolted joints, or thin high strength adhesives, the load transfer is smoother and local stress concentrations are avoided.

Sika has proven to be a stable partner, providing all the necessary information required for a professional design approach. The Sika Elastic Bonding booklet has provided thorough advice for selecting the right adhesive type for the right geometrical parameters, such as the thickness to width ratio of the adhesive cross sections, for structural analyses and for correct adhesion preparation. In the case of new applications, Sika supports how to achieve a joint design to sustain more than 30 years of operational life. For example, by performing adhesion tests and testing the static and dynamic response of the adhesive, thereby allowing any degradation and fatigue effects adjustments to be made to the design. Thus, we have received all static and dynamic mechanical properties required for numerical analyses and for structural assessments, even for dynamic analyses of collision scenarios.

We hand out this booklet to young engineers to provide a sound overview on the design principles and basic requirements. The recommendations given in this booklet allow for a solid start of the design process, even for first time users.

Dr Alois Starlinger
Member of the Management Board,
Head of Vehicle Authorization,
Structural Analysis and Testing at Stadler

INTRODUCTION

INERTIA CAN BE VERY USEFUL. It's what keeps objects in motion along a straight line, forever, unless acted on by an external force. Indeed this is why spacecraft can travel over long distances without additional power.

By contrast, industrial businesses need to overcome inertia, to create innovation and change towards higher performance and more efficient solutions for their products. Elastic bonding has proven it can provide opportunities for innovation in many industrial applications, with bonded assemblies in cars, commercial vehicles, building facades and more.

Engineers not using adhesives or new to elastic bonding may ask 'I'm used to designing and producing components with mechanically fixed joints. I know elastic bonding has some potential advantages, but where to start?' As with inertia, it's only the initial push that's difficult. So to help, Sika has compiled this handbook which takes you, step by step, through elastic bonding.

By reading this handbook you will gain an understanding of elastic adhesive bonding, its advantages, how it compares to other fastening techniques and how to design and calculate the strength of elastic bonded joints. You will learn about production methods and equipment and you will find a number of useful tools including formulae and examples.

The Sika specialists who have compiled this book are experts in elastic bonding, not only in design, calculation and testing, but also in implementation. They are available to support you in successfully adopting the technology.

Using elastic adhesives you can design and produce innovative and technically sophisticated products that generate high added value. So if you are an industrial engineer wanting to create opportunities, read on. If you are an industry manager or owner, it is recommended that you read at least the first two chapters and then share this book with your engineering team.

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1 INNOVATION THROUGH ELASTIC BONDING

ADHESIVE BONDING IS AN ESTABLISHED FASTENING TECHNOLOGY that complements traditional fastening methods in manufacturing industries. The introduction of elastic adhesives created new opportunities for product innovation.

One example is the introduction of elastic adhesive for direct glazing in the automotive industry in the late 1970s, which increased the torsional stiffness of vehicles and the safety of occupants. Bus and coach manufacturers soon followed suit as elastic bonding proved to be ideal for assembling large parts such as roofs and windows. Among other benefits, elastic bonding helped to reduce corrosion by allowing fully painted components to be joined.
An example of innovative solutions in the buildings sector is the introduction of elastic adhesives to bond window frames directly to glass, providing technical and aesthetic benefits, which allowed manufacturers to increase the area of glass with narrower frame dimensions. The added bonus of improved thermal insulation and noise reduction made it an ideal solution.
So, with these examples in mind, it will come as no surprise that elastic adhesive bonding has since grown to become an essential technology in an increasing range of manufacturing industries.

But before we go into more detail, let's define what is meant by elastic bonding.

1.1. DEFINITION OF ELASTIC BONDING

Elastic adhesive bonding, in essence, involves the bonding of two materials by an interfacial layer of permanently flexible adhesive that also performs a sealing function. Whenever different materials need to be joined, tolerances bridged, or large components assembled, elastic adhesives are the preferred solution.
ISO 21194 refers to elastic adhesives and sealants as products "with a minimum elongation at break of 100 % and a modulus of elasticity of maximum 10 MPa". The elongation at break describes the elasticity and the modulus of elasticity describes the stiffness. Elastic adhesives typically have a hardness of 20-60 on the Shore A scale, which is a unit to classify rubber like materials. Door seals for cars, as an example, have a Shore A around 50 or 60.
By contrast, adhesives with lower elongation at break and higher modulus of elasticity are defined as being semi-rigid or rigid.

1.2. USE OF ELASTIC ADHESIVE BONDING IN THE TRANSPORT INDUSTRY

Elastic adhesive bonding with polyurethanes and silane terminated polymers has contributed to innovation in vehicle design since it allows designers to create bold new shapes, combining different materials such as glass, composites, and lightweight metals. But design is only one aspect because increased performance in terms of passenger comfort, reduced weight, production efficiencies and more, all contribute towards elastic adhesives becoming the go-to solution for assembly in all types of vehicle manufacturing industries.

1.2.1 DESIGN FREEDOM

Aesthetic appearance and travel comfort of cruise ships, yachts, trams, buses, trucks and trains is important to fleet operators because it helps attract more passengers. Elastic bonding also helps engineers reduce vehicle weight, resulting in a higher payload or numbers of passengers. In addition, a bonded body assembly possesses greater torsional stiffness, dampening road noise and vibration.
Elastic adhesives resist loads, caused by thermal expansion of different materials, and enhance vehicle durability in a range of climatic situations, from cold arctic winters to heat wave summers.

Fig. 1.1
Modern trams owe their stylish looks to a combination of glass, engineered plastics and lightweight metals, bonded together with adhesives

Fig. 1.2
Yacht with many elastic bonding applications

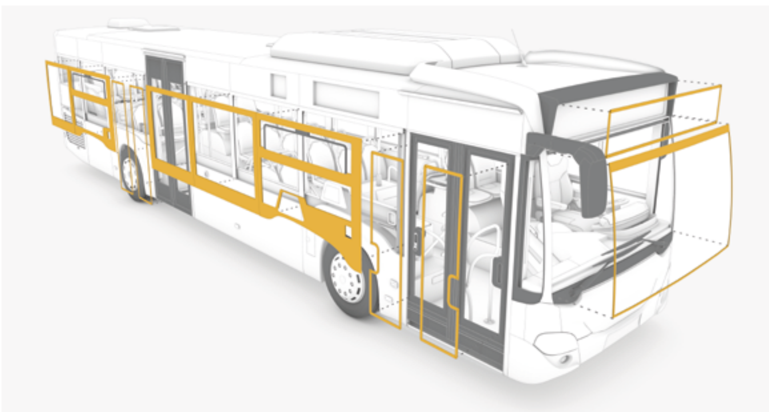


Fig. 1.3
Glass adhesive bonding applications on a modern bus

1.2.2 MODULAR VEHICLE ASSEMBLY

Modular assemblies, such as driver's cab or roof elements, are fitted out completely before being bonded to the chassis with adhesive. Since neither heat nor mechanical processing of the parts is required for joining, sensitive components such as paintwork, interior trim, wiring harnesses or windows can be assembled in advance. This makes the manufacturing process flexible and more efficient compared to other fixing methods.

Fig. 1.4 Train driver cabins with pre-assembled windscreens

1.2.3 WEIGHT SAVING

Elastic bonding plays an integral part in keeping down overall vehicle weight. The combined weight of a structural frame and a non load bearing sheet metal skin can be reduced by adhesive bonded body panels that contribute directly to the vehicle's structural strength. This allows the use of a lighter frame or lightweight materials. As an example, the latest generation trams weighs up to a third less than their predecessors, meaning reduced material and lower running costs.

1.2.4 LONG TERM DURABILITY

The durability of elastic adhesives, especially long term dynamic strength, can be demonstrated by numerous reference examples. Buses with adhesive bonded window glass date back to the 1980's. Covering several million kilometers, the adhesive joints have continued to function perfectly.
From time to time, vehicles are disassembled to check the long term dynamic performance of adhesive joints. Sika participates in such reviews to check the condition of joints and product performance. The insights gained are used to enhance future developments and guidelines. One example is a 20 year old train of the Swiss Federal Railways SBB, whose inspection results are described in a later chapter.

Fig. 1.5
Intercity train ICN

1.2.5
LOW MAINTENANCE

When, for instance, a floor is bonded to a chassis, the corrosion protection layer remains intact and is therefore less prone to corrosion. By comparison a mechanically fixed floor requires holes for screws or bolts which compromises the integrity of the joint and ultimately increases maintenance costs. Additionally, while transferring dynamic forces applied to the joint, the layer of elastic adhesive also acts as a sealant, preventing entry of water, salt, or other corrosive media. Adhesive joints are usually maintenance free, except if they are permanently exposed to chemicals, harsh weathering, or similar. But if, and when, an open sealed joint wears out, it can simply be repaired by replacing the worn layer with fresh sealant.

1.2.6
ECONOMIC EFFICIENCY

In many cases, adhesive bonding can be more economical than conventional fastening techniques. It is also cleaner and uses less energy than other fixing methods. Manufacturing costs are directly proportional to the number of components to be fastened together and adhesive bonding helps to reduce the number of components, supporting a modular approach to design and construction. Elastic adhesives allow thick-layer adhesive bonding which means that larger manufacturing tolerances can be accommodated by simply increasing the thickness of the adhesive layer. This is particularly effective in keeping down production costs. And crucially, this can be done with elastic adhesives without reducing the mechanical strength of the joint to any significant extent.

1.3. USE OF ELASTIC ADHESIVE BONDING IN THE FACADE AND WINDOW BUSINESS

Elastic silicone adhesives have become an industry standard in the manufacture and installation of facade elements. In this process, structural glass panels are adhesively bonded to metal frames. This creates design freedom for engineers who can choose where and how they want to place the adhesive joint. Modern skyscrapers are impressive examples of this. Robust performance at high temperature, in addition to excellent weathering and UV resistance, make silicone adhesives ideal for such applications.

The high elasticity of elastic bonded joints ensures that deformations are adequately compensated for, despite stiffening the construction. Facades are able to withstand extreme conditions such as desert temperatures or high dynamic loads created by extreme weather events including hurricanes and typhoons, or other extreme events such as earthquakes and burglary attempts.

1.3.1 DESIGN AND ARCHITECTURAL TRENDS

Glass façades, windows and doors, are part of the building envelope and are strongly influenced by architectural trends. In fact, glass has been representative of modern architecture for several decades. Open and light filled rooms are certainly perceived as creating a pleasant environment and, due to this trend, glass elements are becoming larger and larger. One of the consequences is that load bearing frames must become equally massive to transfer the loads into the building.

Elastic bonding plays a key role here as it makes it possible to keep the frame slim by bonding the frame directly to the glass. Thanks to the uniform stress distribution of elastic bonding, a stiffening of the unit can be achieved without overloading the now narrower frame. This has opened up new design possibilities for the manufacturers of windows and doors as well as for the manufacturers of the final glazing units. The results are clear, elastic bonding has become a key element in the ongoing trend towards flawless and transparent glazing elements.

Fig. 1.6
Futuristic design

The Shard in London stands out with its unique monolithic design. The four sided structural glazing is impressive with its frameless appearance. The large format glass panel elements are bonded to an adapter profile with an elastic silicone adhesive. These prefabricated facade modules are then attached to the support structure, giving the façade a flat and harmonious glass surface.

Fig. 1.7 The Shard, London

Similar principles are used for the construction of movable glass elements such as windows and doors. Despite their large dimensions, these elements are eminently rigid, which is particularly important to prevent problems with closing and opening.

Fig. 1.8 Adhesive bonded windows with slim frames

1.3.2 BONDING DIFFERENT MATERIALS

New material combinations are increasingly used in the construction business. This means that assembly techniques must be suitable for a wide range of materials, including coatings on glass or metal. As these materials undergo temperature change, they expand or shrink differentially according on their thermal expansion coefficient. Elastic adhesives must compensate for the differential thermal movements occurring between the substrates and must distribute static and dynamic loads evenly into the material without localized stress peaks. This defines elastic adhesives as the ultimate joining technology for fragile materials such as glass.

The below illustration demonstrates this using a simplified glazing construction bonded with a silicone adhesive. It is assumed that a mineral glass pane is bonded to an aluminum frame. When assembled with adhesives at 20 °C, both parts are of equal length. But the thermal expansion of aluminum is nearly three times greater than that of glass. During summer or winter, this can result in a length difference of approximately 2.2 millimeters between glass and aluminum, equivalent to around 1.1 millimeters per bond line, assuming free expansion on both sides. A 6 millimeter layer of silicone adhesive for structural glazing would be sufficient to compensate for such deformation without introducing critical stresses into the glass or damaging the adhesive.

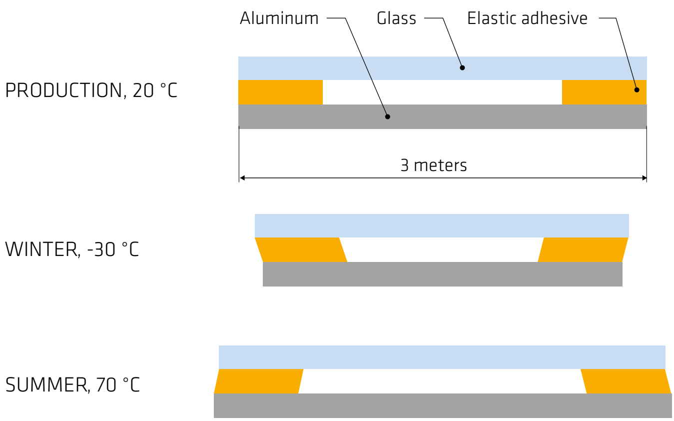


Fig. 1.9 Thermal expansion in a glazing construction (schematic).

Please see the chapter regarding calculations for further details about thermal expansion and maximum allowed elongation values. It is important to note that it is not only thermal expansion that determines the needed thickness of adhesive layer. There are also other factors to take account of.

1.3.3 TOLERANCE COMPENSATION

Manufacturing tolerances for building components are usually in the millimeter range. This is especially true for large glass components, some of which are curved and over 10 meters long. Elastic bonding technology allows manufacturers to bridge gaps of this magnitude without loss of strength, since the actual thickness of the elastic adhesive layer does not have a critical effect on the strength of the joint. Variations in thickness can easily be compensated for by increasing the adhesive thickness layer.

1.3.4 SOUND DAMPING

Rigid glass and metal frames transmit external traffic noise and sound relatively well into the interior of the building. By contrast, elastic adhesives form a damping layer between the glass and the frame that can attenuate noise. The human ear is able to distinguish a sound difference of 3 dB. So with an elastic adhesive, that can lower traffic noise by 5 to 7 dB, you will notice the difference.

1.3.5 ENERGY SAVING

Elastic adhesives have a relatively low thermal conductivity, so they act as an insulator between glass and metal frame. This property is especially effective with elastic adhesives that are used in thicker layers compared to rigid adhesives.

The $\boldsymbol{U}$ value or thermal transmittance coefficient indicates how much thermal energy flows through a particular component. The lower the value, the better the insulation of the building component. It has been shown that the use of elastic adhesives in facades and windows can significantly reduce the $\boldsymbol{U_f}$ value ($\boldsymbol{U}$ value frame) by redesigning the frame (e.g. smaller frame, less steel). As an example, the $\boldsymbol{U_f}$ value of a particular mechanically fixed glass unit was reduced by 60 % when bonded with an elastic adhesive.

1.3.6 DURABILITY AND SAFETY

Façades bonded with elastic silicones are made to last, making it possible for façade elements to withstand extreme conditions such as high temperatures or intense loads caused by hurricanes, typhoons, earthquakes and cope with sudden heavy impact loads such as explosion. Due to its deformability, the elastic adhesive layer behaves well under sudden loads or short term stress peaks.

Whether the bond survives a load case undamaged depends on its strength and, above all, on the fracture work. Fracture work is the product of the force necessary to break the bond and its displacement. Due to the high elongation capacity of elastic adhesives, bonded windows can even withstand burglary attempts because there is simply not enough room to stretch the adhesive sufficiently to break the joint.

1.3.7 ECONOMIC EFFICIENCY

There are numerous commercially available systems to dispense adhesive and assemble components. Depending on the actual requirements, the adhesive application can range from manual through to fully automatic processes. In principle, the systems can be selected such that the most efficient and flexible production is achieved. Selecting the ideal solution saves time, improves reproducibility and ultimately lowers unit production costs.

A practical example to illustrate this is the window manufacturing process. Traditionally the glass is mechanically supported and clamped in the frame profile, a manual process step that is difficult to automate. Elastic adhesive bonding facilitates the use of robots to position the insulating glass into the window frame and apply the adhesive in one fully automatic process.

2 COMPARISON WITH OTHER FASTENING TECHNIQUES

ADHESIVE BONDING, WHETHER ELASTIC OR RIGID, FUNDAMENTALLY DIFFERS FROM TRADITIONAL MECHANICAL FASTENING METHODS. An understanding of the salient characteristics of mechanical fastening methods compared to adhesive bonding helps support mastery of joining technology.

2.1. TECHNOLOGY OVERVIEW ADHESIVES

There are a number of factors that need to be taken into account in order to successfully employ elastic bonding technology. When used correctly, the many advantages of adhesive bonding can be capitalized upon.

2.1.1 DESIGN FREEDOM

A wide spectrum of materials can be combined in bonded elements, to achieve aesthetics and performances that no single material can achieve. Because the substrates are combined with adhesive spread across the joint area, the forces the joint is subjected to are uniformly distributed. Increased load demands can be met by increasing the bonded area of the joint, without stress peaks, even when using thin and lightweight substrates.
Manufacturing tolerances of components means there are gaps of varying width between substrates. This can be compensated, even up to several millimeters, by means of high viscous, gap-filling adhesives. And the wide variety of available adhesive mechanical properties, from stiff to highly flexible, allows

a choice of adhesive to support the design requirements of the finished product at the optimal level.

2.1.2 ENHANCEMENTS

Elastic adhesives compensate for relative movement of large parts caused by thermal expansion, thus preventing bulging or damage to the components. Because elastic adhesives are polymers, they can absorb vibrations, reduce or prevent galvanic corrosion and work as electric insulators or conductors, as well as thermal insulators.

2.1.3 PROTECTION

Mechanical fixation often entails damage to surfaces and substrates to fix them together. By contrast, adhesives do not require any mechanical processing such as drilling or clinching. In parallel, surfaces remain smooth and without visual distortion. And when dealing with delicate substrates, most adhesives can be applied at temperatures that do not affect thermo-sensitive substrates.

2.1.4 CONSIDERATIONS

The choice of adhesives and scope of the application needs to be aligned to the desired result, which requires a good working knowledge of adhesive technologies. Consideration must be given to the limitations as well as the benefits to select an ideal solution. As an example, thermal and chemical resistance may not be as high as with mechanical joining technologies. This is important to carefully evaluate when changing to bonding technology.

The mechanical properties of adhesives are generally lower than mechanical fixing. Therefore the design strength and resistance to effects such as creep requires correct dimensioning of the adhesive bond. Adhesives may degrade over time due to adverse temperature, sunlight, chemicals, and mechanical stresses. To reach the expected service life, the joint must be designed accordingly.

In the bonding production process, adhesives start to react immediately after application, so the application and assembly process must be planned, executed and controlled to accommodate the adhesive process window.

Some adhesives, cleaners and primers may be classified as hazardous substances and therefore need to be used safely according to the instructions in the Safety Data Sheet.

2.2. COMPARISON WITH OTHER TECHNOLOGIES

Fig. 2.1
Comparison of joining technologies

APPLICATION CRITERIA	BOLTS, RIVETS, SCREWS, ETC.	SPOT WELDING, WELDING, ETC.	ADHESIVE BONDING
Joining together dissimilar materials	good	fair	excellent
Computer modeling of joints	excellent	excellent	good
Thermal distortion	excellent	fair	excellent
Susceptibility to corrosion	fair	good	excellent
Sealing of joint	fair	good	excellent
Waiting time between assembly and handling strength	excellent	excellent	good
Temperature resistance of joint	excellent	excellent	fair
Ease of disassembly	excellent	fair	good

Legend: = excellent, = good, = fair

2.3. MATERIALS AND STRESS DISTRIBUTION

Design and appearance are important, but assemblies must also be high performance, durable and cost effective. The following describes how elastic bonding can contribute to this.

2.3.1 CHOICE OF MATERIALS

The need to join different materials together is often associated with lightweight construction, which deliberately exploits the specific performance characteristics of the various materials used. Synthetic materials and plastics, either fiber-reinforced or made up into composites, are also widely used in lightweight constructions. This means that fastening techniques must accommodate a wide range of different materials. With elastic adhesives, materials of low intrinsic strength can be fastened together flexibly and without localized stress peaks, resulting in a strong, load bearing adhesive joints.

2.3.2 DISTRIBUTION OF STRESS WITH BOLTS

To ensure a durable connection and to maximize service life, an even distribution of stresses throughout the assembly is essential, particularly in the immediate vicinity of the joint. Conventional mechanical joining methods such as welding, riveting or bolting cause localized stress peaks. The distribution of stresses can be assessed by computer-aided calculation. The colour contours reveal how loads distribute and stress concentration. The pictures below shows a high concentration of stresses around the bolt. A similar pattern can be seen with joints secured by rivets and spot welds.

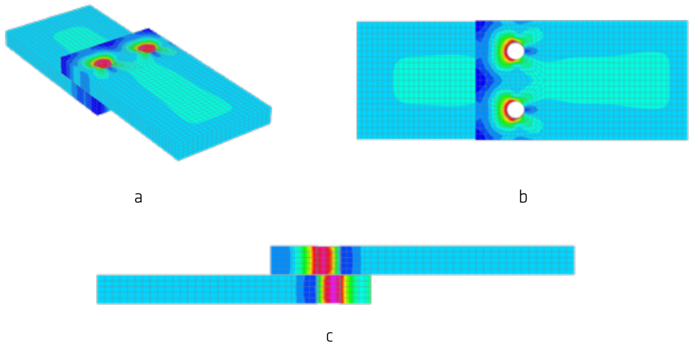


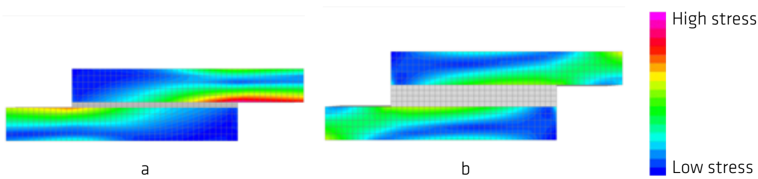
Fig. 2.2 Stress distribution bolt.
a: perspective view
b: plan view
c: section view

2.3.3 DISTRIBUTION OF STRESS WITH RIGID AND ELASTIC ADHESIVE BONDING

We have learned that adhesive bonding distributes forces more uniformly within the joint. In the case of rigid adhesives, with a relatively thin bond line, the stresses tend to concentrate at the end of the joint overlap. This effect is more pronounced in substrates with a low modulus of elasticity, such as plastics. Making the bond line wider by increasing the overlap does not necessarily lead to higher strength in these cases because the forces still tend to transmit to the ends.

In the case of thick-layer elastic adhesives the stresses in the bonded substrates are more uniformly distributed along the bond line, so that the whole of the bond face is contributing to the strength of the joint. Hence, the breaking strength of elastic adhesive bonds is more directly proportional to the area of the bond face. In practice, this means elastic bonded joints can be designed to transmit higher forces simply by increasing the area of the bond face. The pictures below illustrate the stress concentrations in the substrates within rigid and elastic bonds.

Fig. 2.3
Stress in substrates joined by
a) rigid adhesive bond line
b) elastic adhesive bond line



2.4. MANUFACTURING PROCESS

2.4.1 WORKING CONDITIONS

Impact on health and the environment are important when evaluating new technologies and products. Welding and mechanical fastening processes can create undesirable noise levels, emissions, such as fumes and dust. By contrast, adhesive bonding is a relatively noise free joining method. Some adhesives, and any necessary surface preparations, may generate volatile and potentially hazardous chemicals. However, the risks can be fully mitigated by using the adhesives as directed with proper safety precautions.

The use of silane terminated silicone adhesives, solvent free pretreatments and the latest generation of polyurethane adhesive with minimal diisocyanate, such as Sika's Purform® technology, can further improve occupational safety.

2.4.2 SHEET METAL VEHICLE BODIES

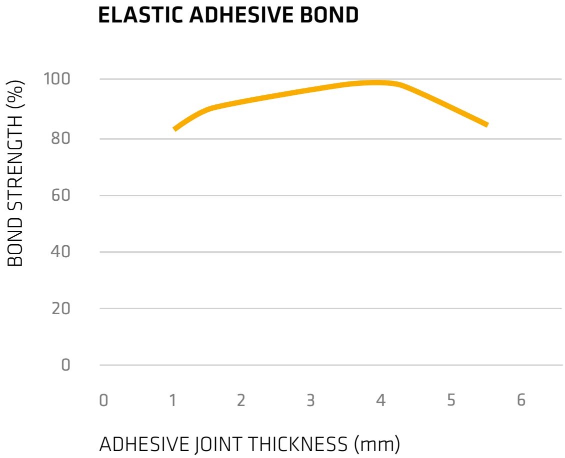
The sheet metal skins of vehicle bodies are sometimes spot welded onto a structural frame. These welds create a series of dimple marks in the metal surface, which then have to be filled and rubbed down in a separate operation to produce a smooth finish. With adhesive bonding, the metal surface remains completely flat and free from distortion, thereby eliminating the labor intensive work and emissions associated with weld refinishing processes, creating important cost savings in terms of time and energy.

2.4.3 BONDING AND SEALING IN ONE STEP

Welding creates high temperatures and heat within the weld area and leads to thermal distortion, deformation and breakdown of the material's internal structure. Correcting this damage is usually done by sanding or dent removal, which is costly and labor intensive. Therefore, in serial production, such post-treatment is only carried out where it cannot be prevented. None of this corrective work is necessary with adhesive bonding because high temperatures are avoided and adhesives do not alter the components.

2.4.4 TOLERANCE COMPENSATION

Manufacturing tolerances of components for the transport industry are usually several millimeters. This applies particularly to large components made from glass, such as curved windshields, or plastics, such as roof modules.
Where structural support is provided by a steel or aluminum frame, the tolerances of dimensionally large components may exceed a centimeter. Elastic bonding technology bridges gaps of this order without any relevant loss of strength.



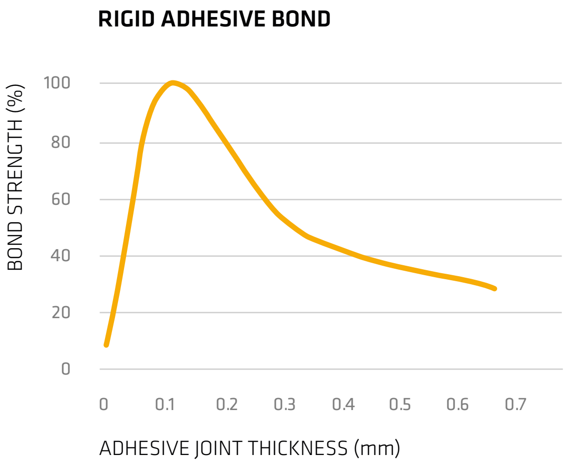


Fig. 2.4
Bond strength versus adhesive thickness

2.4.5 STRENGTH DEVELOPMENT

Adhesive joints do not immediately achieve their full strength, it develops over time. But importantly regarding process cycle time, in many cases assemblies have sufficient handling strength to move to the next processing stage immediately, or after a short time. It is worth noting that the bonding process itself can take significantly less time than conventional joining methods.

Process times have been further reduced by the development of fast cure adhesives and by adhesives with a high instant grab. Such technologies comprise two stages. The first, a rapid initial strength development that reaches a level sufficient for the assembly to be handled and moved on through the production cycle. The second, a slower stage of cure, which provides the ultimate strength and the long term temperature resistance required for the proposed application.

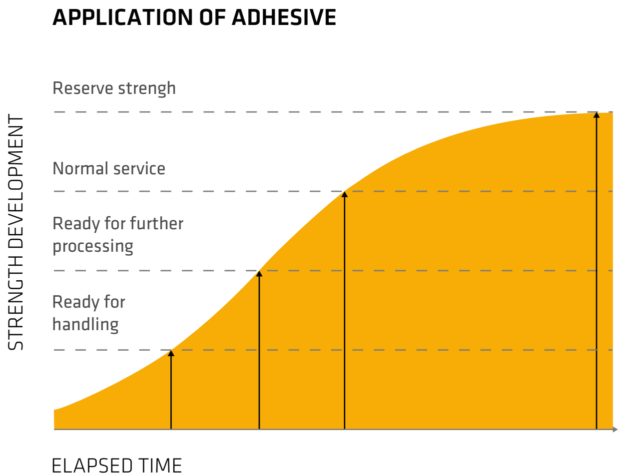


Fig. 2.5 Strength development of adhesives

2.4.6 MECHANICAL PROPERTIES

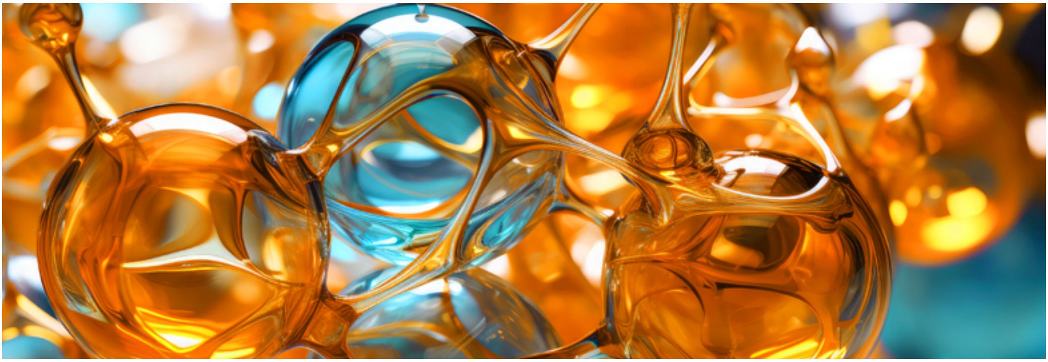
ISO 21194 refers to elastic adhesives and sealants as products “with a minimum elongation at break of 100 % and a modulus of elasticity of maximum 10 MPa”. These values place the mechanical properties of elastic adhesives in between sealants and hard setting adhesives. This accounts for the fact that elastic bonded joints can transfer forces and distribute stresses evenly. In contrast to rigid adhesive joints, elastic adhesive layers undergo some deformation when loads are applied to them. This property is extremely useful in terms of damping vibrations or taking up any displacement resulting from the application of an external force. Exposure to heat, for example, may result in differential thermal expansion, causing adhesively bonded components to move relative to one another.

2.4.7 TEMPERATURE RESISTANCE

The temperature resistance of an adhesive bonded joint is not as high as a mechanically fastened joint. In many areas of application however, the service temperature of the finished assembly remains below 100 °C, which is below the critical temperature range for most adhesives.

At the same time, the possibility of exceptional circumstances must be considered, for instance in the event of fire. In such cases, additional mechanical fixtures may be used for safety support to prevent damage and injury from falling components or to prevent potentially hazardous leaks for example, from gas meters. In applications with high temperature exposure, the use of silicone adhesives is commonplace. Typical silicones can withstand up to 180 °C and specially formulated heat resistant types beyond 300 °C.

3 ADHESIVE TECHNOLOGIES EXPLAINED



COMPETENCE CAN BE DESCRIBED AS HAVING RELEVANT KNOWLEDGE AND THE ABILITY TO EMPLOY IT SUCCESSFULLY. So here we focus on describing adhesives, especially elastic adhesives, their chemistry, core functions and limitations. Acquiring this knowledge assists the successful selection and implementation of adhesives best suited to any given application.

3.1. OVERVIEW

3.1.1 OVERVIEW

The chemical base on which adhesives and sealants are manufactured determines the properties of the product. Since ISO 21194 defines elastic adhesives and sealants as products "with a minimum elongation at break of 100 % and a modulus of elasticity of maximum 10 MPa" we need to understand what that means in adhesive product terms. One way to show the differences is to plot mechanical properties in a diagram that illustrates strength versus elongation at break for various adhesive types.

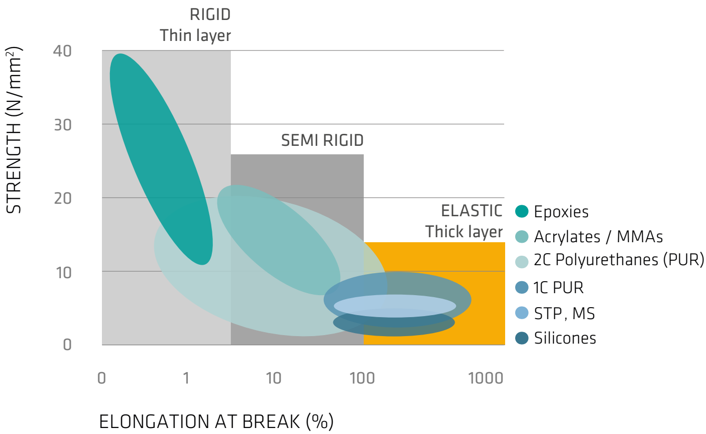


Fig. 3.1
Adhesive mechanical properties comparison

3.2. POLYURETHANE

Polyurethane is a versatile material used in numerous products. Reactive polyurethanes are used as sealants, adhesives, coatings and foams and can cover an extensive range of mechanical properties and densities.

3.2.1 CHEMISTRY

Polyurethane adhesives and sealants are typically formulated as 1- or 2-component materials. They are generally viscous material compounds comprising a non-volatile reactive diisocyanate based prepolymer that, in the case of 1-component composition, reacts with moisture in the air. When curing, the water molecules react with the isocyanate group of the prepolymer, which further reacts with a second prepolymer and forms a durable cross-link between the two prepolymers. The reaction produces carbon dioxide as a byproduct which is released into the environment.
In the case of 2-component adhesives, the main components are polyisocyanates that are mixed in a given ratio with a polyol based hardener to cross-link and form a durable polyurethane elastomer.

3.2.2
SAFE HANDLING

Polyurethane adhesives and sealants are based on prepolymers that contain diisocyanate groups as reactive materials and a certain amount of lower molecular diisocyanates.

In common industrial practice, polyurethane sealants and adhesives are used safely and result in minimal, normally below detection level, hazardous components.
Naturally, it is of paramount importance to follow the instructions in the Safety Data Sheet to ensure safe use and handling, as it is with all chemicals. Special attention to occupational safety must be observed when applying adhesive at high temperatures, such as the case with reactive hot melt polyurethanes, or on dimensionally large areas.
Engineered to minimize diisocyanate monomer content, Sikaflex® Purform® adhesives and sealants deliver all the benefits of industry leading polyurethanes, but with less than 0.1 % monomeric diisocyanate for better health protection and occupational safety. Purform® is the foundation for a new generation of best in class Sika products that perform stronger, last longer, and meet the health and safety needs of the future. In particular, Sikaflex® Purform® solutions do not require users to conduct the European REACH health and safety training for diisocyanates.

3.2.3
BOOSTER AND 2-COMPONENT

Curing speed in general, and assurance that large joints through-cure within a reasonable time, are important aspects. Booster adhesives utilize water based pastes which are mixed into the adhesives at the point of application, designed to accelerate the cure speed. Sikaflex® Booster adhesives can be cured with air moisture as explained in the previous section or by SikaBooster® in a 50:1 mixing ratio. Such products reach the same ultimate performance with or without use of booster.
Products with a mixing ratio from 1:1 to 10:1 can only be used as “classic” 2-component products (base and hardener). However, they are easier to mix homogeneously due to their higher mixing ratio.

3.2.4
SNAP CURE PERFORMANCE

Polyurethane adhesives are formulated as 2-component materials for faster curing, independent of moisture and to reach higher final material performance. Typically 2-component polyurethanes achieve a pot life to cure time ratio of 1:4, which means the time available to apply the product is one quarter of the time the product needs to cure. If such products are very fast curing formulations, the time for application can become too short for effective handling, they are simply too fast to handle.
Latest developments based on "Curing by Design" feature, have allowed the creation of snap curing adhesives where the reaction is delayed and doesn’t start immediately after the two components are mixed, but remains in a paste consistency for longer, and then cures extremely fast. An open working time

to cure time ratio of nearly 1:1 is achievable with such systems, creating a step change benefit in terms of bonding cycle time.
The below chart shows the ratio between time and curing strength for a regular 2-component product compared to a product with Sika's Curing by Design technology. It shows how the Curing by Design product starts to cure later, but with almost instant effect.
It will be interesting for engineers to note that the snap cure principle, as described here with polyurethanes, can also be incorporated into 2-component silane terminated polymer adhesives.

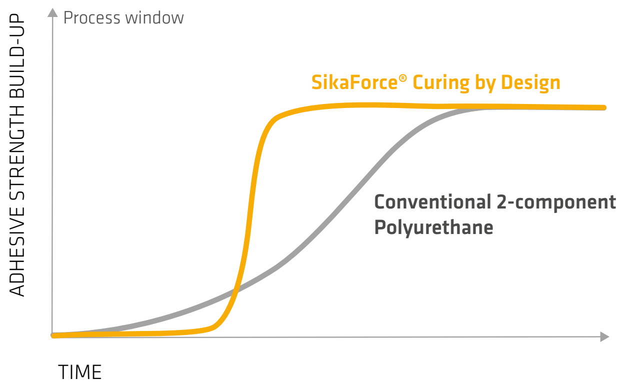


Fig. 3.2
Advantages of Curing by Design

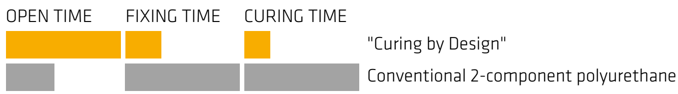


Fig. 3.3
Process time duration comparison

3.2.5 LATENT HARDENERS

Since 1-components polyurethanes cure by contact with air moisture and release carbon dioxide as a byproduct, the formation of unwanted bubbles may occur during the curing of the adhesive bead. This mostly happens if products are used at elevated temperatures and in high humidity environments. Certain adhesives therefore contain latent hardener which influences the chemical reaction mechanism and suppresses the formation of carbon dioxide. With such compositions, polyurethane adhesives and sealants can be formulated to function well under relatively high temperature and humidity conditions.

3.2.6 HEAT CURING

1- and 2-component adhesives that can be cured by exposure to a specific elevated temperature, often called thermo-activated or heat-activated, contain a hardener which is encapsulated or blocked and which is subsequently released when exposed to a design temperature of 80 °C or higher. Such products are particularly useful when a baking process follows the application, such as paint finishing, or in cases where an immediate cure is required for faster cycle times.

3.2.7 BENEFITS AND LIMITATIONS OF POLYURETHANES

BENEFITS	LIMITATIONS
Versatile adhesives and sealants can be formulated, ranging from very high elasticity sealants with low strength to high strength and modulus adhesives suitable for structural load bearing applications.	High temperature and humidity application releases carbon dioxide during the curing reaction, which can lead to bubble formation if the material is applied incorrectly or outside the intended temperature and humidity range. Products specially formulated to compensate for this are described in previous sections.
Durable and well proven in many applications. They can withstand heat and humid conditions well. Additionally, they can be formulated for high chemical or weathering resistance.	Through curing of 1-component adhesive, as for all moisture curing products, depends on the accessibility of the bead to moisture and on the temperature. For large beads it can take some days to fully through-cure. Sikaflex® Booster technology and 2-component products eliminate the dependency on air moisture but curing speed still depends on the temperature.
Adhesion to a wide range of substrates can be achieved because they generally bond well to various materials and can be formulated for primerless adhesion to glass, paint, plastics and metals.	UV resistance is low. They can be formulated to withstand weathering and other factors at the surface of a joint, but the bond face needs to be protected from UV light.

3.3. SILANE TERMINATED POLYMERS

Silane terminated polymers (STP) and silane modified polymers, also known as modified silane, can be found as sealants and elastic adhesives in industrial manufacturing.

3.3.1 CHEMISTRY

Silane terminated polymers and silane modified polymers are a particular group of adhesives and sealants that use a polymer binder material containing reactive silane groups. For silane modified polymers, the polymer backbone is a polyether, while for silane terminated polymers, the polyether, in a first step, is reacted into reactive polyurethane and, in a second step, the isocyanate groups capped with silanes. As a result, silane terminated polymers allow the composition of adhesives with higher strength compared to silane modified polymers.
The products are typically moisture curing 1-component but can also be formulated as 2-component for faster curing. When curing, the silane groups are hydrolyzed with water, the formed silanol groups can condensate with each other to build a stable polymer network. The curing reaction typically releases methanol which is released into the environment.

3.3.2 SAFE HANDLING

Silane terminated polymers and silane modified polymers are free of diisocyanates, but they contain components that can result in allergic reactions. Typically, products based on these technologies are composed as low to medium strength adhesive sealants. An improved health and safety profile and adhesion to a wider range of materials are two reasons why the technology can be beneficial for applications that demand higher material properties.

3.3.3 EPOXY HYBRIDS

Hybrids of different technologies have the ability to create unique performance features and combinations of desirable properties. Especially the combination of silane terminated polymers and epoxy technology can result in sealant adhesives with improved adhesion and corrosion resistance, or flexible epoxy adhesives. The combination of these two technologies means adhesives can accommodate a broader adhesion range, exhibit higher strength, and cure faster.

3.3.4 THERMAL CONDUCTIVITY

Silane terminated polymers are generally compatible with highly conductive fillers. Such adhesives and gap fillers are important, for example, in the efficient cooling of battery cells in electric vehicles. For battery and vehicle makers, the efficiency of a product, which means the thermal conductivity per millimeter of material thickness, is a key selection criterion.

3.3.5 SUSTAINABILITY

Curing of silane terminated polymers is typically catalyzed using organotin based components and releases methanol, both of which are undesirable. The adhesive industry has therefore developed products that are free of tin and phthalate plasticizers. Technologies that release ethanol instead of methanol while curing are available too. However, such products, while feasible for manufacturing industry, come with two main disadvantages, cost and curing speed. Additionally, methanol has not yet become a focus area of regulators hence, such products are not widely available.

3.3.6 2-COMPONENT AND BOOSTER

As with polyurethanes, curing speed and the assurance that also large joints are fully cured within a reasonable time, are important aspects for using silane terminated polymers in industrial manufacturing.
Sikaflex® Booster adhesives can be cured with air moisture as explained in the previous section or by SikaBooster® in a 50:1 mixing ratio. Such products reach the same ultimate performance with or without use of booster.
Systems with a mixing ratio of 10:1 can only be used as 2-component products. However, they are easier to mix homogeneously due to their higher mixing ratio.

3.3.7 SNAP CURE PERFORMANCE

The snap cure principle, as described with polyurethanes, can also be incorporated into 2-component silane terminated polymers.

3.3.8 BENEFITS AND LIMITATIONS OF SILANE TERMINATED POLYMERS

BENEFITS	LIMITATIONS
Wide adhesion range to a variety of substrates without the use of surface treatment. For load bearing applications or when used on porous substrates the use of surface treatment significantly increases durability	Mechanical performance is not as high as some other technologies. Typically good adhesive sealants, reaching more than 3.5 MPa in lap-shear strength are rare.
Isocyanate free composition means a more user friendly health and safety profile. For example, there is no special requirement from the European Union to pass a worker health and safety training, as is the case with many, but not all, polyurethanes.	Through curing occurs more slowly in cold and dry conditions because, as moisture curing products, they require two to three times as much water as polyurethanes. In large beads full cure can take several days. Sikaflex® Booster technology and 2-component products eliminate the dependency on moisture but curing speed still depends on temperature.
Weathering resistance is naturally high. Special products with built in stabilizers maintain their color even after years of exposure to sunlight.	UV Resistance is low. While they can be formulated to withstand sunlight and other factors at the surface of a joint, the bond line needs to be protected from UV light.
No bubbling of the released methanol, as byproduct of the curing reaction, even if used at extremely hot and humid conditions.	

3.4. SILICONES

The polymer chains of silicone adhesives consist of silicon and oxygen, which distinguishes them from their organic counterparts. Silicones have excellent stability towards heat, UV light and weathering conditions and are widely used, for example, as adhesives, sealants, medical purposes and applications with special thermal or electrical requirements.

3.4.1 CHEMISTRY

The reactive polymer in silicone adhesive and sealants is typically polydimethylsiloxane. Like other technologies, 1-component silicone adhesives and sealants require moisture from the air for curing. During the curing process, byproducts such as acetic acid, an oxime or an alcohol is released. In 2-component systems, the catalyst, which contains the required curing agents, is separated from the base component until applied. There are three common technologies as follows.

Acetoxy silicones are 1-component type and are the most common silicone grade for general purpose sealants used as a sanitary or do it yourself material. They can be identified by their distinctive vinegar odor once applied. Care must be taken on which substrates these sealants are used due to the corrosive nature of the acetic acid byproduct.

Oxime silicones are also 1-component type which release oxime byproducts and their use has become more strictly regulated because of the carcinogenic risk. Methyl ethyl ketoxime systems have been banned from do it yourself applications in Europe. On the other hand, oxime systems can exhibit excellent shelf life stability and were used in many applications as both sealants and adhesives.

Alkoxy systems come as 1- and 2-component types and are currently considered state of the art for high performance silicone adhesives and sealants. Compared with other technologies, the methanol or ethanol byproduct is more pleasant in odor and does not cause corrosion. 2-component silicones are almost exclusively based on alkoxy technology and are typically free of organic extender oils. Such products are used as engineering silicones for the manufacture of façade elements and insulating glass. Silicones also find their way into a wide variety of applications in home appliance and high temperature applications due to the excellent stability towards demanding conditions.

3.4.2 SAFE HANDLING

With the ban of methylethyl ketone oxime in Europe, more and more silicone sealant and adhesive suppliers switched from oxime to the more environment, health and safety compliant alcoxy silicones. More recently the shelf life stability and performance of alcoxy systems have been equaled, making this technology fit for the future.

3.4.3 BOOSTER

There is an increasing focus on environment, health and safety. The chemical components of SikaBooster® are less critical in that respect compared to typical B-components of 2-component products, which have more stringent labeling due to their catalysts.

3.4.4 SPEED

With a higher degree of automation in home appliances, solar energy, façades and insulating glass assembly lines, the demand for faster 2-component silicone solutions has increased. This demand has resulted in a series of new products from adhesive and sealant suppliers to fulfill user needs.

3.4.5 BENEFITS AND LIMITATIONS OF SILICONES

BENEFITS	LIMITATIONS
Excellent UV and weathering resistance thanks to their inorganic backbone. Joint surface do not crack and colors are stable. They maintain their adhesion and mechanical performance even when the bond face is exposed to UV light.	Mechanical performance is lower than some other mentioned technologies. Low cost formulated silicones suffer from poor tear propagation resistance and some have a short shelf life. With the right formulations, high performance products can be created, and utilized in applications such as façade elements, insulating glass, solar elements or structural glazing.
Broad service temperature range, generally resistant to heat of up to 200 °C. Specially formulated products for use in extreme conditions remain elastic at -70 °C and withstand more than 300 °C without losing their function. In addition, silicones have an inherently high fire resistance, perfect candidates for fire resistant assemblies.	Through curing, as for all adhesive that rely on moisture, depends on accessibility of the bead to moisture and the temperature. 1-component silicones cure to a maximum joint depth of 15 millimeter. For deeper joints, boosted systems or 2-part materials are used.
Chemical resistance against a range of aggressive environments and media, such as some acidic substances, water and organic solvents.	Not paintable and low cost silicones also tend to leach extender oils and plasticizers, resulting in shrinkage of the joint and bleeding on porous substrates. Small traces of silicone contamination can cause fisheyes on painted surfaces, which explains the reluctance of introducing any silicone in paint body shops.

4 BONDED JOINT DESIGN

THE SUCCESSFUL AND COST EFFECTIVE APPLICATION OF ADHESIVE BONDING TECHNOLOGY CRUCIALLY DEPENDS ON CORRECT JOINT DESIGN. The joint must be capable of transmitting all forces that apply, compensate for tolerances, accomodate thermal dilatations and withstand static loads.

4.1. GENERAL DESIGN REQUIREMENTS

Proper adhesive joint design requirements, while taking into consideration the behavior of elastic adhesives, are:

- Correct joint ratio (width:thickness) ideally between 1:1 and 5:1
- Avoid 3-sided adhesion
- Minimum joint thickness of 3 mm
- Substrates must be parallel and should have even surfaces

4.1.1 LOAD CASES

The figures below show five of the most common load cases. While shear, tensile and compressive forces usually cause an even distribution of stress in the joint, bending and torsion typically lead to high stress concentration, which can cause adhesive breakage.

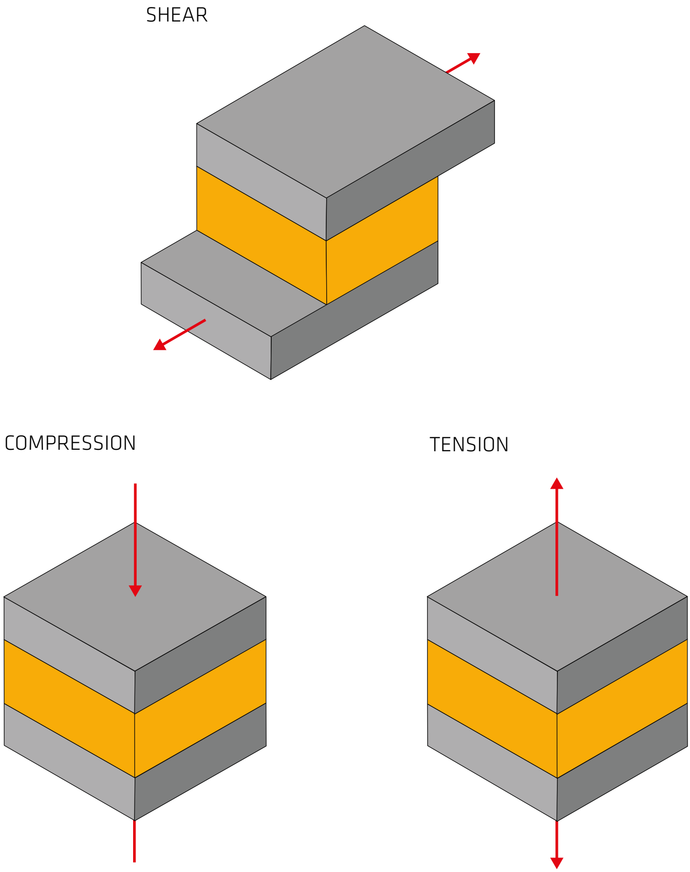


Fig. 4.1
Recommended load cases

The two load cases below involve high peel and shear forces that can lead to delamination or adhesive breakage. They are best avoided or used only with caution.

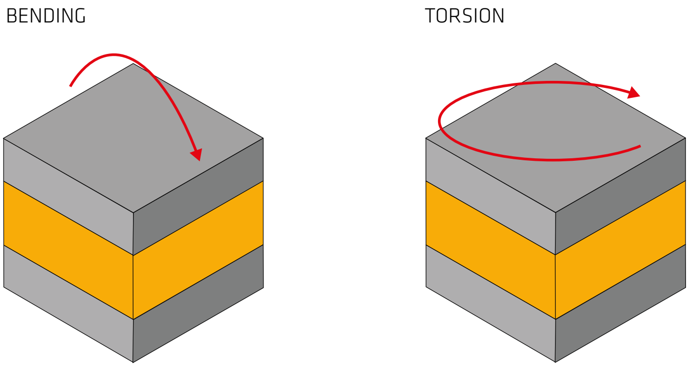


Fig. 4.2
Not advisable load cases

4.1.2 REDUCING STRESS

Increasing the bonded area can often reduce the stress in the bond line when pure tension, shear or compression forces are involved.
The following picture shows an angled flange with a vertical glass. The flange is painted, the glass has a ceramic frit. Calculations show that the area of the adhesive bond is too small to support the static load of the glass. Such overloading can lead to creep, meaning the adhesive bead will give way over time, causing the glass to sink permanently or, even worse, the adhesive detaches from the substrate.

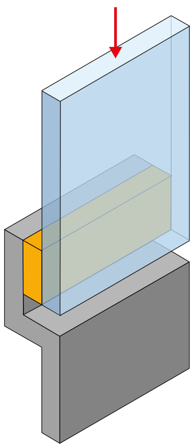


Fig. 4.3
Angled flange with vertical glass

So, what options are available?
Selecting an adhesive with significantly higher strength, and thus higher modulus, is one option. However, this assumes that the substrate paint and the glass

can withstand the higher forces caused by the stiffer adhesive (see figure 4.4). In practice, there are narrow limits to this approach.
Another option would be to use setting blocks that carry the load of the glass. These blocks must be designed in a way to take over the dead load and avoid local stresses which could possibly lead to glass breakage.
Increasing the joint by using a larger glass would increase the bond width but also reduce the gap between the glass and flange. This could cause contact between the glass and flange due to the desired movement of the joint materials because of thermal movement or other external factors.

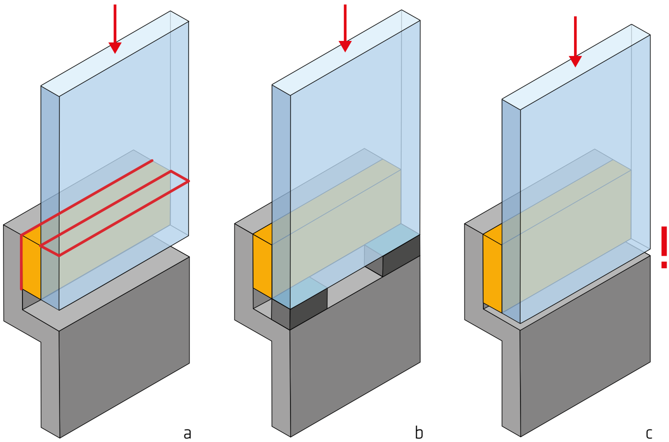


Fig. 4.4
a: Stiffer adhesive
b: Setting blocks
c: Larger glass

Alternatively, the bonding area could be increased by making the flange wider (see figure 4.5). This reduces the stress in the bond line. In such a case it is important to ensure UV protection of the bond face, so the adhesive joint must not be wider than the ceramic frit.

A final option could be to fill the gap between glass edge and flange with a sealant or adhesive. Since this extends over the entire length, it would support the glass without risk of glass breakage. However, it would be important to use a product with a suitable hardness. The width of the joint must be designed in way to cope with the movement of the different substrates within the allowable movement capability of the sealant used.

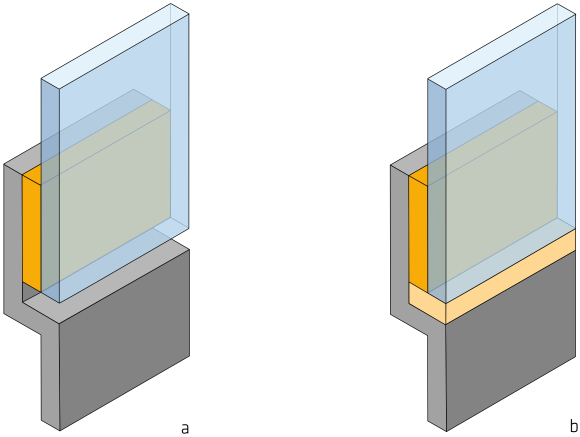


Fig. 4.5
a: Wider flange
b: Gap filled

4.1.3 THREE SIDED ADHESION

Elastic adhesives move with the two parts they join. If the product adheres to a third surface, this can limit its freedom of movement. Movements caused by, for instance, thermal expansion of the joined parts may cause peak stress and thus damage the bond. Three sided adhesion should therefore be avoided.

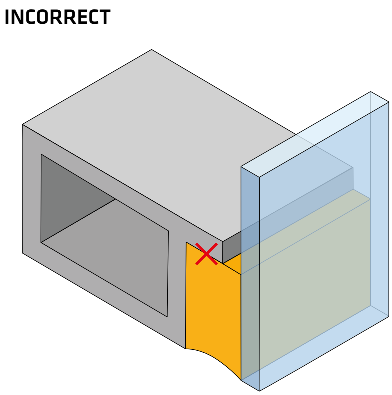


Fig. 4.6
Three sided adhesion

4.2. DESIGN RULES

Beyond the mechanisms of load transfer, other aspects need to be considered to ensure joints fulfill their function.

4.2.1 DRAINAGE CONCEPT

Rain or condensation can cause permanent standing water if ventilation or drainage is inadequate. This can affect the durability of bonded joints, especially in conjunction with substrates that are prone to corrosion. The solution to this is not difficult but can be overlooked.

The first example is a roof panel which is adhesively bonded to a perimeter framing profile using two adhesive beads for higher strength. The solution is to interrupt the lower adhesive bead at regular intervals. This allows the cavity between the beads to be drained and ventilated. Otherwise, water could accumulate due to condensation or unnoticed water penetration. This in turn could cause corrosion and loss of adhesion over time. In addition, the sealing joint is located on the outside of the sloping part of the roof. This allows water to drain freely.

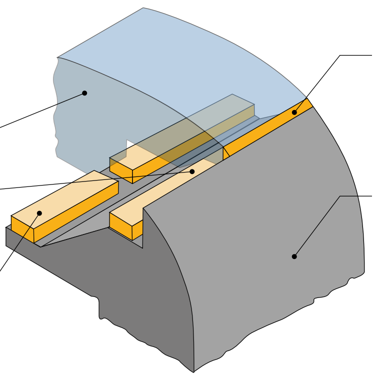


Fig. 4.7 Example of how to prevent water ingress in a roof panel joint

Another simple, yet effective method is shown in the pictures below. The adhesive bond line on the left is not flush with the frame that the glass is bonded to. Condensing water can accumulate in the resulting void and, over time, damage the frame's corrosion protection and compromize adhesion. The example to the right shows the same situation with the void filled with an additional, small bead of adhesive or sealant. Here, water accumulation is prevented because water can effectively drain away.

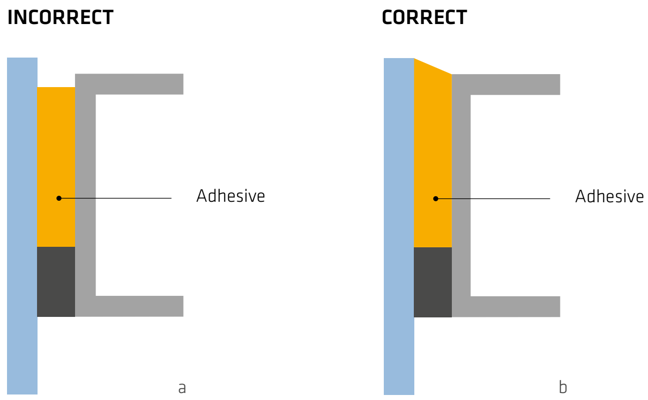


Fig. 4.8
a: Risk of water accumulation
b: Avoiding of water accumulation

4.2.2 JOINT DIMENSIONS

Many bonding applications can be planned by means of standard dimensions. The below graphs illustrate what dimensions usually lead to good results when bonding side windows on vehicles such as buses.
These dimensions are usually sufficient to absorb movement between glass and frame during vehicle operation. In addition, the application of adhesives and sealants, as well as repair, can be accomplished. The values must be checked in each case, but serve as a generic guide which is proven in practice. For unsupported glass the static dead weight loads must also be considered and bigger joint dimensions should be expected.

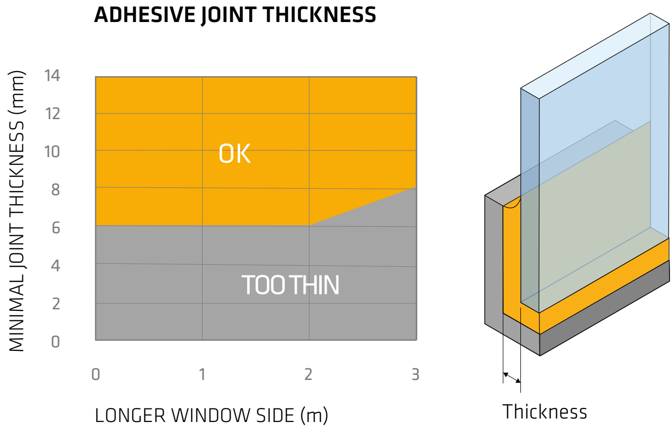


Fig. 4.9
Adhesive joint thickness

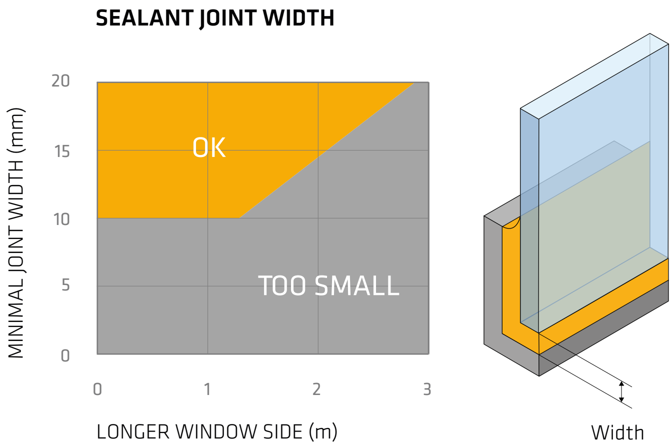


Fig. 4.10
Sealant joint width

When deviating from the values shown, the properties of elastic adhesives must be considered. These must be applied thick enough so that the elastic behavior is not compromised. While a higher value is mostly not critical, a too small value can lead to problems.

4.2.5 HIGH STANDARDS OF LIGHTWEIGHT CONSTRUCTION

Today it is not just the window glass that is bonded with elastic adhesives, but the body panels and floor pan as well. This has enabled vehicle manufacturers to use all kinds of lightweight and mixed material combinations without compromising on safety, functionality or comfort. Consequently, lightweight construction in the industry has now attained a very high standard.

4.2.6 SHEET METAL VEHICLE BODIES

The sheet metal skins of vehicle bodies are sometimes spot-welded onto a structural frame. These welds would create a whole series of dimple marks in the metal surface, which then had to be filled and rubbed down in a separate operation to produce a smooth finish. With adhesive bonding, the metal surface remains completely flat and free from distortion and makes this labor-intensive process unnecessary. Anti-corrosion paint coatings remain intact, which prolongs the life of the assembly. The natural damping properties of the elastic adhesive extend the vehicle's operating capabilities. Finally, adhesive bonding opens up the possibility of using lightweight materials such as aluminum, glass-fiber-reinforced plastics (GRP), sandwich panels or other composites.

5 CALCULATING THE STRENGTH OF ELASTIC ADHESIVE JOINTS

ANALYTICAL AND COMPUTER-AIDED CALCULATIONS PLAY A KEY ROLE IN THE DESIGN OF BONDED JOINTS. Calculating the mechanical strength of these joints can be complex and time consuming, but the procedures are well known and quite easy to apply in many situations.

5.1. INTRODUCTION IN CALCULATIONS

Calculation methods valid for rigid joints apply only in part to elastic joints. When building prototypes or setting up test arrays, engineers have to base their calculations on reference values which, in most cases, are only approximations from technical data such as tensile lap-shear strength, with appropriate safety margins factored into the calculations. As a result of numerous studies by technical universities and adhesive suppliers, engineers now have access to an ever increasing inventory of experimental data to calculate the strength of an adhesive bond.

5.2. STRENGTH MEASUREMENT

The strength of an adhesive is generally stated in terms of its tensile lap-shear strength τ_{RT}, determined by performing tests on a single-lap adhesive joint. The test piece is subjected to a shearing stress by applying a tensile load centrically to the two lapped substrates.
Depending on the adhesive technology, the adhesive strength can also be expressed in terms of tensile stress σ_{RT} obtained by testing in tension with samples called H-specimens.
Both lap-shear strength τ_{RT} and tensile strength σ_{RT} are typically determined for a defined adhesive layer dimension at room temperature (23 °C / 50 % relative humidity) at a defined deformation speed, under ideal laboratory conditions.

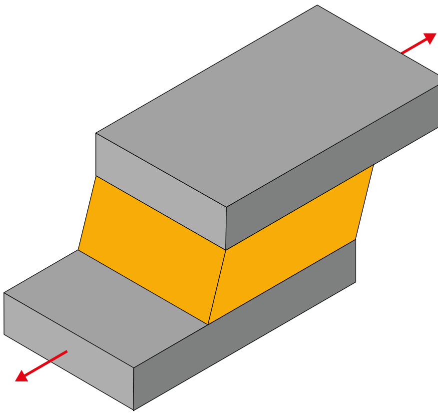


Fig. 5.1 Single lap adhesive joint used in tensile lap-shear test

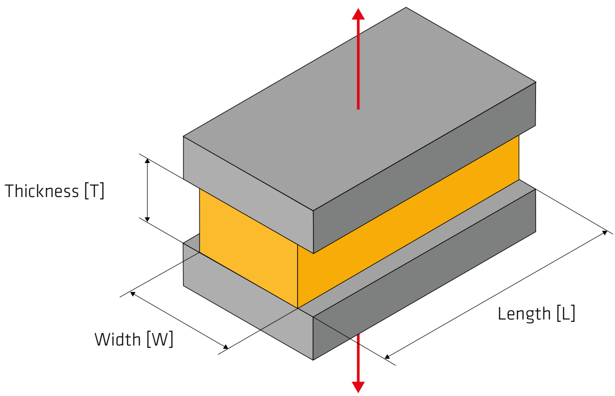


Fig. 5.2 H-specimen adhesive joint used for tensile tests

5.3. SAFETY FACTORS

When calculating the design strength of larger bonded assemblies, engineers have to reduce laboratory figures by an appropriate design safety factor γ_{Des}. Even where all the adverse influences on an adhesive joint are known, it is still advisable to factor in an additional margin of safety to allow for any variations in quality during the manufacturing process, which ensures the results of strength calculations will always be on the safe side. Depending on joint function and possible joint failure risks, it is common practice to consider γ_{Des} values ranging from 1.5 to 2.5 or higher. National and international standards and user relevant requirements can provide specific values depending on the application and adhesive technology used.
To evaluate joint capacity, better results are obtained by carrying out tests on the actual components or assembly. In many cases, it is necessary to test the adhesive joint by applying different load configurations before the final design calculations can be performed.

5.4. REDUCTION FACTORS

The strength and the mechanical properties of an elastic adhesive joint are highly dependent on external factors including:

- Service temperature
- Load duration. I.e. the duration of exposure to the load
- Number of times the joint experiences a load. I.e. the fatigue effects
- Aging conditions
- Speed of the load applied
- To a lesser extent, dimensions of the joint

To account for these factors, the design strength of a joint can be quantified only after applying the further below explained reduction factors $\boldsymbol{f}_i$ of the tensile strength $\boldsymbol{\sigma}_{RT}$ or lap-shear strength $\boldsymbol{\tau}_{RT}$, according to the concepts explained in the following sections.
The diagrams below show the dependency of a typically used elastic polyurethane adhesive under the different conditions. To a certain degree, the shown behavior is also valid for other elastic adhesive technologies, but detailed information must be requested from the specific adhesive manufacturer.

5.4.1 TEMPERATURE EFFECT f_T

The strength of the joint decreases with rising temperature. The reduction factor for the effects of temperature exposure on an adhesive can be determined by tensile lap-shear tests or tensile tests. It is important that joint service temperatures are kept far away from the glass transition temperature of the adhesive, where a fast and significant change in mechanical properties occurs. For typical elastic adhesives, this temperature can be as low as -50 °C.

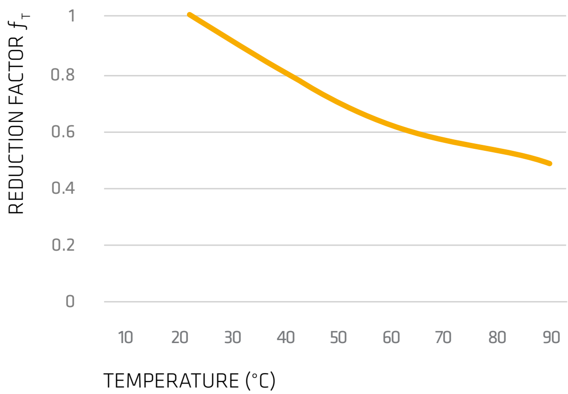


Fig. 5.3 Reduction factor: Effect of temperature for polyurethane

5.4.2 LOAD DURATION AND CREEP f_S

The longer the duration of the load applied to the joint, the lower the strength it offers. The results of creep rupture tests on single-lap joints can be used to determine the reduction factor for an adhesive bond subjected to constant static loading. In constant load tests of this kind, creep deformations are observed in the adhesive layer.

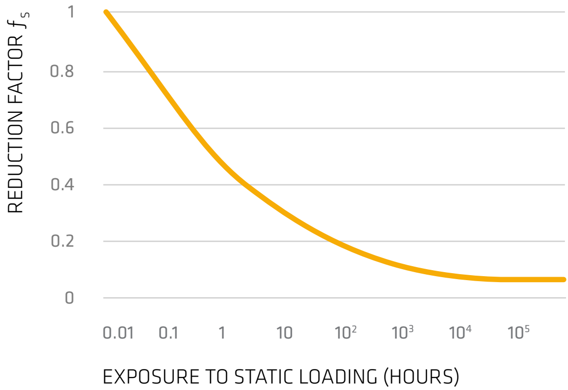


Fig. 5.4
Reduction factor: Effect of duration of static load for polyurethane

5.4.3 FATIGUE f_F

The fatigue behavior of adhesive bonds is tested by subjecting tensile lap-shear samples to dynamic load cycling. When the test values are plotted on a Woehler chart, the appropriate reduction factor for prolonged exposure to dynamic stress can be read from the chart. As the number of cycles is increased, the amount of alternating shear stress that the adhesive layer can withstand is progressively decreased until no further reduction in strength is observed after this point.

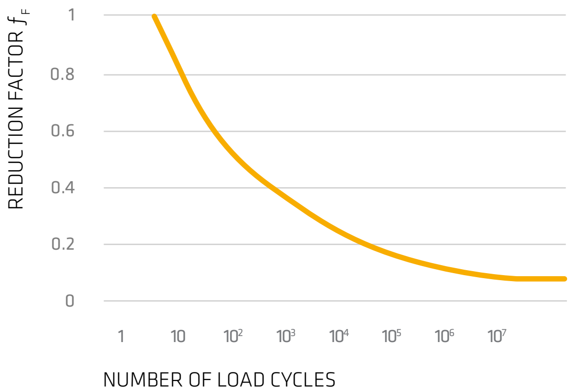


Fig. 5.5
Reduction factor: Effect of prolonged exposure to dynamic stress

5.4.4 AGING f_A

During its service life, the joint is exposed to aging conditions that can reduce the strength of the adhesive. Among others, aging effects can be due to water contact, weathering, exposure to high humidity at high temperatures and chemicals, such as cleaning agents.
Depending on the adhesive used and the target application, the reduction factor for the effect of aging can be determined by lap-shear tests or tensile test on samples exposed to specific aging cycles.

5.4.5 LOAD SPEED

The load speed can also have an impact on the joint strength. The higher the load speed, the higher the strength offered. This influence is taken into account especially in extreme design scenarios where impulsive loads are involved. I.e. blast loads, crash impact, etc., where standard test speeds are not representative.

5.4.6 JOINT DIMENSIONS

Joint dimensions affect joint strength to a minor degree only. For elastic adhesive applications, we can assume that, given the same joint thickness, the bigger the joint width, the higher the strength. And, given the same width, the higher the thickness, the lower the strength.
Within typically recommended joint dimensions for elastic bonding, the influence of joint dimensions on strength is considered negligible.

5.4.7 STANDARDS

It is important to note that all reduction factors f_i mentioned above are typically determined by using tensile lap-shear tests, but local or international standards can provide different test methods depending on the specific application and the actual adhesive technology used. As an example, EAD 0900-10-0404 and EN 15434-1 evaluate silicone joint performance in Structural Sealing Glazing applications by different test methods and samples.

5.5. LOADS, LOAD COMBINATIONS AND DESIGN STRENGTH

5.5.1 STRESS CALCULATION

When assessing the performance of an elastic joint in a bonded assembly, the tensile and shear stress transferred to the joint must be calculated based on the loads that can apply.

In simplified equations, the tensile and shear stress transferred to a joint can be calculated as follows:

Fig. 5.6 Equation: tensile stress

$$\sigma = \frac{F_T}{A}$$

Fig. 5.7
Equation:shear stress

$$\tau = \frac{F_S}{A}$$

Where $\boldsymbol{F_T}$ and $\boldsymbol{F_S}$ are the tensile and shear forces that apply to the joints and A is the bonded area to consider and $\boldsymbol{A}$ = joint length x joint width.
Typical loads to consider are wind loads, live loads, dead loads, impact and others.
To determine the equivalent stress $\boldsymbol{\sigma_V}$ for a thick-layer elastic adhesive, normal stress theory may be used. This is commonly employed for components that are mechanically restrained from undergoing expansion.

Fig. 5.8
Equation: equivalent stress

$$\sigma_v = 0.5\sigma + 0.5\sqrt{\sigma^2 + 4\tau^2}$$

5.5.2 THERMAL EXPANSION

For all bonded systems where substrates of different materials are joined together, effects of different thermal dilatations must be taken into account. Temperature changes produce linear expansion or contraction of the bonded substrates imposing different movements to the joints. If the different movements cause shear movements $\boldsymbol{\Delta_S}$, the joint thickness must be checked by the following formula:

Fig. 5.9
Equation: shear movement

$$\Delta s \leq \alpha_{i,S} t$$

If the differential movements cause elongation or compression $\boldsymbol{\Delta_T}$ of the joint, the joint thickness must be controlled as follows:

Fig. 5.10
Equation: tensile movement (elongation or compression)

$$\Delta t \leq \alpha_{i,T} t$$

With
$\boldsymbol{t}$ = joint thickness
$\boldsymbol{\alpha_{i,S}}$ = allowable deformation for shear movements, dependent on adhesive and frequency of the imposed displacements.
$\boldsymbol{\alpha_{i,T}}$ = allowable deformation for elongation/compression axial movements, dependent on adhesive and frequency of the imposed displacements.

Depending on adhesive and application, local and international standards can provide different design method to account for effects of thermal dilatations. As an example, the effect of shear differential movements due to thermal dilatations can be assessed by checking the shear stress transferred to the joint:

Fig. 5.11
Equation: shear stress

$$\tau_{TH} = \Delta s \frac{G}{t}$$

With $\boldsymbol{G}$ = shear modulus of the adhesive.

As a general principle, the higher the joint thickness the higher the movement the joint can accommodate. The table below shows typical values for elastic polyurethane adhesives.

	THERMAL MOVEMENT	ACCIDENT	LOADING	NORMAL SERVICE
	Discounting restraining force of adhesive	For example derailment	And un-loading	Operation (dynamic stresses)
$\alpha_{i,T}$: Tension or compression (relative to width of adhesive / sealant layer)	20 %	20 %	20 %	10 %
$\alpha_{i,S}$: Shear (relative to thickness of adhesive / sealant layer)	50 %	50 %	50 %	25 %

Fig. 5.12
Maximum permis-sible movement

5.5.3 LOAD COMBINATIONS

When all loads acting on the system are identified, load combinations must be defined. It is unlikely that all identified loads apply simultaneously on the system at their maximum magnitude. Depending on the application, standards can provide information about load combinations and level of load interaction to consider.

For each load combination, different boundary conditions apply. For instance, maximum wind peak and temperature limited to 40 °C, highly frequent wind load and temperature at 80 °C, etc. Therefore, for each load combination the values of the reduction factors $\boldsymbol{f}_i$ previously mentioned must be reassessed and different design strengths defined.

For each load combination, the final design strength, to ensure joint integrity over service life, can be defined as shown in the example below:

Fig. 5.13
Equation: Design strength shear

$$\tau_{Des} = \tau_{RT} \frac{f_T \cdot f_S \cdot f_F \cdot f_A}{\Upsilon_{Des}}$$

Fig. 5.14
Equation: Design strength tensile

$$\sigma_{Des} = \sigma_{RT} \frac{f_T \cdot f_S \cdot f_F \cdot f_A}{\Upsilon_{Des}}$$

Where the value of f_i must be selected based on careful evaluation of the load conditions the joint can be exposed to in service life in the specific load combination.
Users and engineers checking the joint and system integrity are responsible to define the boundary conditions that apply to each load combination.

5.5.4 DESIGN STRENGTH

For each load combination it must be ensured that the actual tensile and shear stress in the joint and their interaction are limited according to the following criteria:

Fig. 5.15
Equation: Comparison tensile

$$\sigma \leq \sigma_{Des}$$

Fig. 5.16
Equation: Comparison shear

$$\tau \leq \tau_{Des}$$

Fig. 5.17
Equation: Design strength

$$\sqrt{\left(\frac{\sigma}{\sigma_{Des}}\right)^2 + \left(\frac{\tau}{\tau_{Des}}\right)^2} \leq 1.0$$

Where σ_{Des} and τ_{Des} are the design strengths of the adhesive to use in the specific load combination.

5.6. CALCULATION EXAMPLES

The following are examples to clarify concepts and calculation approach.
To reiterate, local and international standards can provide different design methods, depending on the application and adhesive used.

5.6.1 SIMULTANEOUS LOAD CASES

The first example is an adhesively bonded bus rear window. The adhesive joint is subjected to static and dynamic loads caused by its weight and driving conditions. These loads are calculated and the results compared with the design strengths to calculate the safety factor.

Fig. 5.18 Typical bus rear window

	DESCRIPTION [UNIT]	VALUE
l_B	Total bond line length [mm]	5400
W_B	Width bond line [mm]	10
A	Bond line area [mm^2]	54 000
m_{window}	Window weight [kg]	17.5
g	Gravity constant [m/s^2]	9.81

Fig. 5.19 Window parameters for the calculation

A bus back window is bonded using a glazing adhesive with a nominal shear strength τ_{RT} of 4.5 MPa. The following simultaneous load case is considered to make an assessment of the safety factor.

- Dynamic tensile load: The window is subjected to an estimated acceleration of a_{yg} = 0.2 g in the horizontal direction due to acceleration or deceleration of the vehicle in standard operation conditions.
- Static shear load: As the window is not otherwise supported, there is a constant static load in shear due to the dead weight of the glass.
- Dynamic shear load: The window is subjected to an estimated vertical acceleration of a_{zg} = 4 g in shear if the bus abruptly hits a pothole during service. This is estimated to happen on average once per day.

	DESCRIPTION [UNIT]	VALUE
a_y	Horizontal acceleration factor [-]	0.2
a_z	Vertical acceleration factor [-]	4

Fig. 5.20 Parameters for case dynamic loads

We can then calculate as follows:
Dynamic load in tension due to acceleration/deceleration in standard service operations of total 10 mio. load cycles. Reduction factor f_F = 0.08

Fig. 5.21 Equation: Tensile value for 10 mio load cycles

$$\sigma_{y-dynamic} = \frac{m_{window} \cdot \alpha_y \cdot g}{f_F \cdot A} = \frac{17.5kg \cdot 0.2 \cdot 9.81\frac{m}{s^2}}{0.08 \cdot 54\,000mm^2} = 0.008MPa$$

Static load in shear due to dead weight of glass. Reduction factor f_S = 0.06

Fig. 5.22 Equation: Shear value for static load

$$\tau_{z-static} = \frac{m_{window} \cdot g}{f_S \cdot A} = \frac{17.5kg \cdot 9.81\frac{m}{s^2}}{0.06 \cdot 54\,000mm^2} = 0.053MPa$$

Dynamic load in shear due to bus hitting pothole. Reduction factor f_F = 0.3 assuming this happens once per day.

Fig. 5.23 Equation: Shear value for "pothole" case

$$_{amic} = \frac{m_{window} \cdot \alpha_z \cdot g}{f_F \cdot A} = \frac{17.5kg \cdot 4 \cdot 9.81\frac{m}{s^2}}{0.3 \cdot 54\,000mm^2} = 0.042MPa$$

Safety factor Υ. Reduction factor f_T for temperature = 0.5.

Fig. 5.24 Equation: Safety Factor

$$\Upsilon = \frac{\tau_{RT} \cdot f_T}{0.5\sigma_y + 0.5\sqrt{\sigma_y{}^2 + 4\tau^2}} = \frac{4.5 \cdot 0.5}{0.5 \cdot 0.008 + 0.5\sqrt{(0.008)^2 + 4(0.042 + 0.053)^2}} = 22.6$$

5.6.2 EOTA ETAG 002

For many years EOTA ETAG 002 has been a well established guideline for calculating silicone joint dimensions in Structural Sealant Glazing applications. Although in 2023 this has been withdrawn, the calculation approach it provides is state-of-the-art and still in use.

As an example, the minimum joint dimensions required in the following system configuration are calculated according to EOTA ETAG 002.

- Glass panel width ***W***= 1500 mm x height ***H***= 3000 mm in portrait orientation
- Glass panel is bonded to aluminum profiles applied along all four sides
- The panel is installed in vertical position
- A maximum wind load $\boldsymbol{p_w}$ = 1.8 kPa applies
- The maximum and minimum temperatures of glass and aluminum frame are $\boldsymbol{T_g}$ = 80 °C / -5 °C and $\boldsymbol{T_f}$ = 55 °C / -5 °C respectively, while bonding of parts occurs at $\boldsymbol{T_b}$ = 20 °C
- The dead load of the panel is mechanically supported. i.e. not transferred by the elastic joint
- The adhesive properties certified according to EOTA ETAG 002 are $\boldsymbol{\sigma_{Dyn}}$ = 0.14 MPa, $\boldsymbol{\tau_{Dyn}}$ = 0.105 MPa and ***G***=0.5 MPa

It must be ensured that the maximum tensile stress in the joint due to wind load is limited as follows:

Fig. 5.25
Equation: Stress due to wind load

$$\sigma = \frac{F_T}{A} = \frac{p_w \cdot W}{2w} \leq \sigma_{Dyn}$$

The minimum joint width ***w*** can be calculated:

Fig. 5.26
Equation: Minimum joint width

$$w \geq \frac{p_w \cdot W}{2\sigma_{Dyn}} = \frac{1.8kPa \cdot 1.5m}{2 \cdot 0.14MPa} = \underline{\underline{9.7mm}}$$

Thermal variations during service life impose shear movements ΔS to the joint. In summer condition:

Fig. 5.27
Equation: Thermal variation summer

$$\Delta_{S,sum} = (\alpha_g \Delta T_{g,sum} - \alpha_f \Delta T_{f,sum})\sqrt{(0.5W)^2 + H^2} = \underline{\underline{0.93mm}}$$

In winter condition

Fig. 5.28
Equation: Thermal variation winter

$$\Delta_{S,wint} = (\alpha_g \Delta T_{g,wint} - \alpha_f \Delta T_{f,wint})\sqrt{(0.5W)^2 + H^2} = \underline{\underline{1.16mm}}$$

With

$\alpha_G = 9 \times 10^{-6}$ 1/K Coefficient of linear thermal expansion of glass
$\alpha_F = 24 \times 10^{-6}$ 1/K Coefficient of linear thermal expansion of aluminum
$\Delta T_{g,sum} = T_{g,max} - T_b$ = 80 °C – 20 °C = 60 °C
$\Delta T_{f,sum} = T_{f,max} - T_b$ = 55 °C – 20 °C = 35 °C
$\Delta T_{g,wint} = T_{g,min} - T_b$ = -5 °C – 20 °C = -25 °C
$\Delta T_{F,wint} = T_{F,min} - T_b$ = -5 °C – 20 °C = -25 °C

It must be ensured that the maximum shear stress in the joint due to thermal variations is limited as follows:

Fig. 5.29
Equation: Maximum shear stress due to thermal variations

$$\tau = \frac{\Delta s \cdot G}{t} \leq \tau_{Dyn}$$

The minimum joint thickness ***t*** is calculated as follows. The larger result of the thermal variations determined above is used as ***Δs***:

Fig. 5.30
Equation: Minimum joint thickness

$$t \geq \frac{\Delta s \cdot G}{\tau_{Dyn}} = \frac{1.16mm \cdot 0.5MPa}{0.105MPa} = \underline{\underline{5.6mm}}$$

According to EOTA ETAG 002 no interaction of wind load and thermal variations must be taken into account. I.e. wind load and thermal variations must not be combined. Therefore, minimum joint dimensions: Width 10 mm x Thickness 6 mm must be applied with the selected silicone adhesive.

5.7. FINITE ELEMENT METHOD IN ADHESIVE JOINT DESIGN

5.7.1 SOLVING PROBLEMS BY NUMERICAL TOOLS

The finite element method (FEM) is a powerful mathematical tool for the numerical solution of a range of structural problems where elastic and plastic materials are used. With elastic adhesive applications, it is often used to evaluate the stress and deformations in the system components, as well as bond lines under defined loads and boundary conditions. Furthermore, the simulation of joints can help to adapt and optimize the design of the joint, meaning the identification of stress peaks and redesigning of the joint following the general design rules to reduce the stress in the particular parts of the joint.
The system to calculate, known as a structure, is subdivided into smaller elements called finite elements that are linked together via nodes. These define a mesh representing a numerical domain where differential equations in multiple variables are solved to answer the structural problem. The higher the number of finite elements, or the finer the mesh, the greater the accuracy of the solution.
In FEM simulations, elastic adhesive joints are typically modeled by springs or volume elements. The two options are explained in more detail below.

5.7.2 MODELLING JOINTS BY SPRING ELEMENTS

The behavior of an elastic joint can be simulated in FE models by use of spring elements, in order to analyze the load distribution and the average stress in the bond line.
The bond line must be subdivided into portions of regular length l_i; each portion is simulated by a spring whose behavior is represented by three constants dependent on joint dimensions and joint stiffness in different directions.

The formulas below allow calculating the constants to consider for each joint segment simulated by a spring element, for tension and shear directions respectively.

Fig. 5.31 Equation: Constant for tension

$$k_{tensile} = \frac{E_{spring} \cdot A_i}{t_i}$$

Fig. 5.32 Equation: Constant for shear - direction 1

$$k_{shear,1} = \frac{G_{spring,1} \cdot A_i}{t_i}$$

Fig. 5.33 Equation: Constant for shear - direction 2

$$k_{shear,2} = \frac{G_{spring,2} \cdot A_i}{t_i}$$

With:

$\boldsymbol{E_{spring}}$ Spring elastic modulus

$\boldsymbol{G_{spring,I}}$ Spring shear modulus in direction i

$\boldsymbol{A_i}$ Area of the joint segment i simulated (width i x length i)

$\boldsymbol{t_i}$ thickness of the adhesive layer i

It is recommended to place the springs at a distance $\boldsymbol{l_i}$ of approx. 50 mm.
The values of $\boldsymbol{E_{spring}}$ and $\boldsymbol{G_{spring}}$ must be derived from tensile and shear tests on specimens having shape and dimensions representative of the behavior of the linear joints.
Considering that the strength limits set for elastic adhesive joints are always associated with small deformations, the material law to implement in a FE model using springs can be simplified as linear without introducing significant inaccuracy.
This also means that $\boldsymbol{E_{spring}}$ and $\boldsymbol{G_{spring}}$ must always be defined in relation to a tensile and shear deformation range; only within the specified deformation range they can approximate the joint behavior by simplified linear-elastic law.

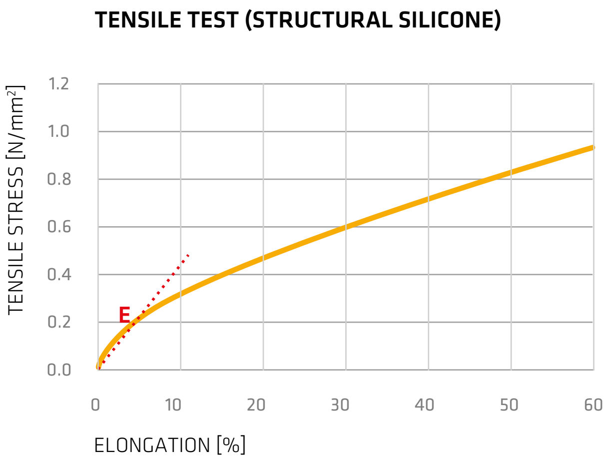


Fig. 5.34 Linear material law in small deformation ranges

The FE analysis of a model including spring elements allows to obtain the tensile force T and the shear force S transferred to the springs. The average tensile and shear stress in the joints can be easily calculated for each spring as

Fig. 5.35
Average tensile stress in the spring element i

$$\sigma_i = \frac{T_i}{A_i}$$

Fig. 5.36
Averages shear stress in the spring element i

$$\tau_i = \frac{S_i}{A_i}$$

For each load combination, tensile and shear stress in the bond line have to be lower than the allowable shear and tensile strengths offered by the adhesive, which depend on load duration, temperatures, exposure to load cycles, etc. according to the strength concepts defined in the previous chapters.
When using spring elements in FE analysis, each spring element must be perpendicular to the bonded surfaces. The nodes of each spring element must be connected directly to nodes of the bonded surfaces and the length of each spring element is identical to the thickness of the joint.
The benefits and limitations of FE simulation of joints by spring elements are as follows:

BENEFITS	LIMITATIONS
The real load distribution along the bond line can be determined	Bending effects within the joint section cannot be modeled
The stiffness contribution provided by the bonded elements, such as glass, frame, etc., can be evaluated	Only average stress within the joint section are extrapolated
The FE model can be built easily and solved within a reasonable computational time	

Spring simulations are recommended for rectangular joints having a width:thickness shape ratio of minimum 1:1 and maximum 3:1. The effect of special joint shape or big joint ratio cannot be evaluated.

5.7.3 MODELING JOINTS USING VOLUME ELEMENTS

Volume elements are well suited for modeling adhesive layers and allow stress and deformation within the joint sections to be represented with great accuracy. The optimum compromise between modeling complexity, computing time and accuracy results from using at least two quadratic volume element or three linear volume elements over the whole joint thickness. It is important to model the adhesive layer at the finest possible resolution, so that its deformation behavior can be accurately represented. The more elements used, the better the understanding of the distribution of stresses within the adhesive layer. If there are no restrictions on modeling complexity or computational time, it is better to increase the number of elements.

The ideal shape for a volume element is a cube; outside this shape, element deviation can be checked by the aspect ratio:

Maximum edge length / Minimum edge length < 3.0
Depending on software, different reliability criteria can apply.

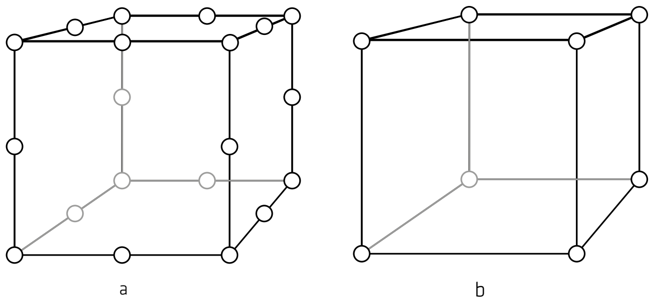


Fig. 5.37
a.) Quadratic volume element
b.) Linear volume element

5.7.4 BENEFITS AND LIMITATIONS IN USING VOLUME ELEMENTS

The benefits and limitations of FE simulation of joints by volume elements are mainly the same offered by springs, but in addition:

BENEFITS	LIMITATIONS
The effect of joint shape/ joint ratio can be evaluated.	Volume simulations usually require big efforts in building the FE model accurately and high computational time.
Bending effects within the joint section can be modeled.	
Stress distribution and stress peaks within the joint section can be evaluated.	

5.7.5 LINEAR AND HYPERELASTIC MATERIAL LAW

In the majority of FE simulations implemented for evaluating joint integrity or system serviceability, the performance of the adhesive joints is controlled by strength criteria. As mentioned before, allowable design strengths are always associated to small deformation ranges where the material behavior can be simplified as linear-elastic. In case of volume elements, the linear-elastic material law can be defined by the following parameters: the elastic modulus $\boldsymbol{E_{vol}}$ and the

shear modulus $\boldsymbol{G_{vol}}$ or the Poisson ratio ν.
The values must be derived from tensile and shear tests on specimens having a shape representative of the behavior of the linear joint.
$\boldsymbol{E_{vol}}$ and $\boldsymbol{G_{vol}}$ always differ from $\boldsymbol{E_{spring}}$ and $\boldsymbol{G_{spring}}$ and must be always defined in relation to a tensile and shear deformation range; only within the specified deformation range they can approximate the joint behavior properly.
In very limited situations, FE simulations are developed to evaluate joint behavior beyond the deformation boundaries of the linear material law.
In such limited cases, the non-linear behavior of the material can be schematized as hyperelastic and expressed by parameters describing deformation energy functions.

The most common hyperelastic material laws used are Mooney-Rivlin, Ogden N=2, Ogden N=3, Neo-Hook, polynomial, etc. that can provide different accuracy and stability results depending on adhesive, deformation range considered, etc.
The parameters to define the material hyperelastic law are defined based on advanced test method that can include uniaxial tests, simple compression tests, volumetric compression tests, planar tension tests and equibiaxial tensile test, or an appropriate selection of them.
Compared to linear material law definition, building up data for hyperelastic law requires advanced competences, tools and test equipment and it is extremely expensive and time consuming. Therefore, availability of hyperelastic data is often limited to selected adhesives.

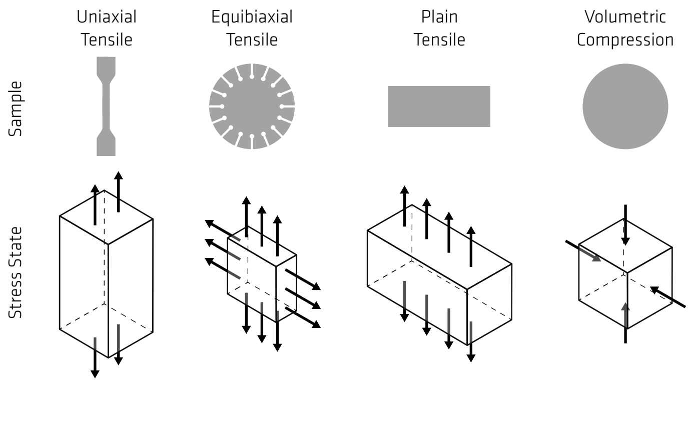


Fig. 5.38 Typical test methods for definition of hyperelastic material data (schematic)

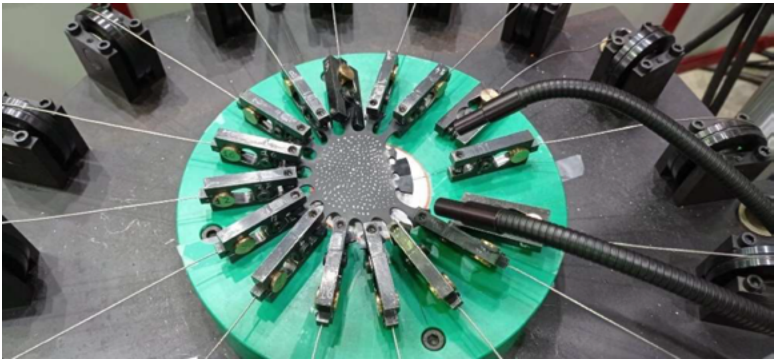


Fig. 5.39 Equibiaxial tensile test

5.7.6 STRESS CHECK CRITERIA

For each load combination, the stress in the volume elements can be evaluated. It is common practice to control the equivalent von Mises stress or the maximum principal stress, according to different possible strength criteria.
The stress in the joint must be limited to the design strengths, which depend on load duration, temperatures, exposure to load cycles, etc. according to the strength concepts defined in the previous chapters.
It is important to mention that different strength limits can be adopted depending on if a linear material law or a hyperelastic material law is used for the FE analysis with volume elements.

5.7.7 IMPORTANT CONCEPTS WHEN DEALING WITH FE ANALYSIS

The following must be kept in mind when dealing with FE simulations of elastic adhesive joints:

- The value of the parameters used to define the material law of the joint depends on the FE element type used. I.e. spring, volume, other. As an example, for the same adhesive and joint dimensions, the elastic modulus to use in springs is different than in volume elements.
- The material law parameters must always be defined within a specific deformation range that defines the validity and/or accuracy level of the given law
- The strength limits used to verify the joint integrity, known as stress check, can depend on the FE element used to simulate the joint. I.e. spring, volume, other
- The strength limits to use for integrity check can also depend on the material law adopted
- Using non-linear geometrical solver is always recommended, without depending on the FE element type and material law used to simulate the joint

Before controlling that the stress in the joints is within the given limit, it is mandatory to control that the joint deformations (springs) or strains (volume) resulting from the FE analysis are within the boundaries specified to define the material law used. If the material law validity is within a deformation range of e.g. 0 % - 10 % and the joint deformation out of the FE analysis is ≤ 10 %, we can proceed with the stress check. If the values are > 10 %, the results are not reliable and the analysis is not sufficiently accurate. Changes in the FE models must be evaluated. E.g. using a different material law, changing the joint dimensions, changing the adhesive, stiffening the system, adding restraints, etc.

It can be useful to compare the benefits derived from each FE type with the time and effort to build it up.

Fig. 5.40 Summary and comparison of methods

	MODELLING TIME	COMPUTATIONAL TIME	EFFORTS TO BUILD UP MATERIAL LAW	RESULT ACCURACY	EFFECTIVE UTILITY
Spring Linear law	Short	Short	Small	Good	Very good
Volume Linear law	Longer	Longer	Bigger	Better	Good
Volume Hyperelastic law	Longer	Longest	Biggest	Best	Fair

5.8. REFERENCES

The content of this chapter is derived from the following references in conjunction with Sika's comprehensive expertise:

- Technical Bullettin DVS 1618 – Elastic Layer Adhesives Used in Rail Vehicle Applications, 2017
- EOTA ETAG 002 – Guideline for European Technical Approval for Structural Sealant Glazing Kits (SSGK) – Part 1, 2012
- Technical Note FKG 01/2021 – Structural Silicone Sealants in Structural Glass Systems, 2021
- Elastic Bonding, Verlag Moderne Industrie, Second revised version edition 2006

6 SELECTING ADHESIVES AND PLANNING FOR THEIR USE

ELASTIC BONDING AND SEALING IS A FORGIVING ASSEMBLY TECHNOLOGY IF KEY ASPECTS ARE RESPECTED. For those used to rigid joining methods such as bolts or welding, elastic behavior might sound contradictory to what they have learned and successfully used so far. So it is useful here to describe the most important topics to consider when selecting elastic products for bonding and sealing components, for example as used in the production of commercial vehicles. These components are often large, made of different materials and already partly prefabricated. Although the focus is on elastic adhesives, many of the topics are valid for other types of adhesives as well.

6.1. MATERIALS TO ASSEMBLE

Selection starts with a series of questions about the materials, such as which components are to be joined? What are the surface properties? Are parts already pre-coated? Are the components translucent or transparent? Is the material sensitive to solvents or plasticizers? This chapter covers these and related topics.

6.2. ADHESION

Adhesive friendly surfaces make the subsequent bonding process easier and more robust. So it makes sense to coordinate the quality of surfaces with the adhesives in question at an early stage. Elastic adhesives and sealants are relatively soft and distribute stresses evenly. They can, therefore, be used effectively on coated materials, such as metals with base or topcoats. Other often used substrates are, for example, glass, ceramic frits, paint primers, powder coatings, glass fiber reinforce plastics, gelcoat, aluminum, steel, ABS, PC or PMMA. PE and PP can only be bonded after suitable pre-treatment, such as the application of a specific primer or physical surface treatment. Substrates that are sensitive to solvents and plasticizers like PS or XPS can be bonded with certain products only.

6.2.1 CONSISTENT QUALITY

Surfaces can alter during manufacturing, transport, handling, aging, exposure to sunlight and weathering. Therefore surface preparation is advisable to ensure stable surface quality for adhesive bonding. Some methods stabilize the surface quality and also offer some protection against environmental influences. Compared with alternative measures to ensure a consistent quality of the material surfaces, like surface quality control and specification or protection from picking up dirt and dust, surface preparation is a cost effective method to assure the final quality of the bond.

6.2.2 PREPARATION

Adhesives require clean surfaces to bond effectively. Cleaning is essential to remove any loose dirt, dust or other contaminants from the surface. Acetone and heptane solvents can remove oil and grease from metals, while alcohol or water based cleaners may be better suited for sensitive substrates like plastics. Physical methods such as plasma also act as a surface cleaner.
Mechanical abrasion such as sandblasting, wire brushing, abrasion with sandpaper or abrasive pads may be needed to remove heavy loose dirt or oxide layers from the surface. Another purpose for mechanical abrasion is to increase the surface area for bonding. Surfaces must be cleaned both before and after abrasion to remove any contaminants.

Fig. 6.1 Manual removal of oxidation layer with abrasive pad

6.2.3 CHEMICAL PRE-TREATMENT

Chemical surface preparation is widely used and is a relatively simple but effective solution. Solutions range from chemical etching to active cleaners which deposit active groups on the surface to film building primers.

Fig. 6.2 Activators and primers with basic application ancillaries

Activators are pretreatment products that include adhesion promoters which chemically interact with surfaces to enhance adhesion. Additionally, their solvents provide a cleaning effect. The layer is typically not visible to the human eye, so for process control, they often contain luminescent dye detectable under UV light.
Primers typically form a layer that can better interlock with the surface of the substrate close cavities and offer compatible surface chemistry to the adhesive. In simple terms, a primer is usually a dilute solution of an adhesive in an organic solvent.

6.2.4 PHYSICAL PRETREATMENT

Some materials, especially plastics from the polyolefin group, may require physical processes such as flame, corona or plasma surface treatment to achieve adhesion. These methods enhance the surface tension and, to a certain extent, also clean the treated surface.
Flame treatment involves exposing the surface to a gas flame for a few seconds. The flame oxidizes the surface and increases the surface energy. The heat of the flame may lead to visible deformation, and users are sometimes reluctant to install flame treatment due to risk of fire.
Plasma treatment is a method where gas plasma is activated to produce a highly excited, ionized gas that reacts with the plastic substrate. The latest plasma technologies allow a surface enhancement with the combination of plasma and adhesion promoters or surface modifiers in one step. The plasma activates both the surface and the molecules, which are then covalently bonded to the surface, resulting in a long term modification of the treated surface's chemical functionality, which remains stable for long enough for a safe and reliable bonding process.

6.3. AVOIDING CRACKING, CORROSION AND DEGREDATION

6.3.1 ENVIRONMENTAL STRESS CRACKING

Components made of thermoplastic materials such as ABS, PC or PMMA must be tested for environmental stress cracking (ESC). The reason for stress cracking is internal and external stresses in the components, which can occur during their production, assembly or in service. These stresses can lead to cracks in the material under the influence of chemicals. For substrates prone to stress cracking, the surface pretreatment and adhesive must be carefully selected. Some elastic adhesives may contain plasticizers that contribute to stress cracking.

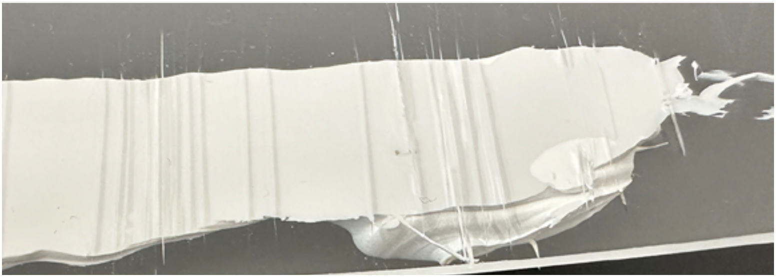


Fig. 6.3 Cracks in a transparent thermoplastic material

6.3.2 CORROSION

Metals that are prone to corrosion need to have adequate corrosion protection, for example a conversion layer or a paint primer. Missing or poor corrosion protection can lead to loss of adhesion. The exact level of required protection depends on the later exposure to corrosive environment. Elastic adhesives adhere well to commonly used corrosion protection methods. Pretreatment primers for adhesives are not primarily corrosion protection solutions, but often do provide an acceptable degree of protection for many applications with low to medium exposure.

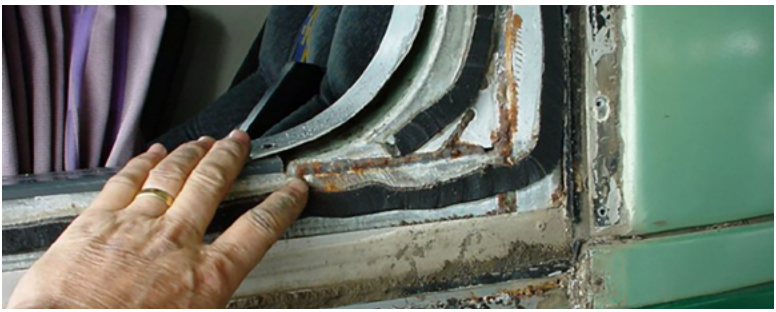
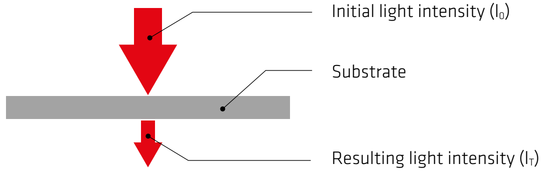


Fig. 6.4 Corroded weld seams due to insufficient corrosion protection

6.3.3 UV DEGREDATION

If the substrates are transparent or translucent, suitable UV protection must be provided to ensure long lasting adhesion with PU and STP/MS adhesives. In the case of glass, this is usually a ceramic screen print which protects the bonding against irradiation and ensures that the bond is discreetly hidden. With the help of transmission measurements, it is possible to check whether the selected screen print is sufficiently light-proof.



$$\text{TRANSMISSION } [\%] = \frac{I_T}{I_0} * 100$$

Fig. 6.5 Equation: Light transmission

UV protection is not required with silicone adhesives for glazing, as these products are highly resistant to UV radiation.

6.4. MECHANICAL DEMANDS

Elastic adhesives are available with different mechanical properties. The stiffness, i.e. the modulus should harmonize with the properties of the component to be bonded.

Softer adhesives are best suited for substrates with low inherent stiffness, such as thin metal sheets. Also, large parts with high coefficients of thermal expansion must be bonded with an adhesive that allows the parts to move without creating excessive stresses in the substrate. The third group is coatings that can peel off when combined with an adhesive that is too stiff.

Stiffer elastic adhesives, on the other hand, add significantly to the stiffness of the assembly without losing the major advantages of elastic bonding. The limiting factor is often the substrate, such as the paint coating, which may not be able to transfer the forces which can occur in the adhesive joint. In this case, it is possible to bond directly to the base material. However, the advantage of being able to bond to a finished component can then be lost.

6.5. JOINT DESIGN

Good design extends durability of the bonding or sealing, poor design shortens it. Correct joint design for elastic bonding supports both joint performance and work processes.
Firstly the joint must be designed such that the adhesive joint is large enough to carry the expected loads, mostly dead weights of bonded parts or external forces. Secondly, adhesives, but especially sealants, must be able to move freely in the required and permissible manner.
Regarding processability, workers must be able to reach the bonding surface with the equipment to apply the adhesive, fill joints and smooth them if necessary. Also if replacement of the components is required later, for instance, in the event of accidental damage of the bonded part, adhesive joints must be accessible to operators with cutting tools and wide enough to insert blades or cutting wires.

6.5.1 DIMENSIONS

Adhesive joints must be large enough to support static and dynamic loads. Reduction factors are used for influencing parameters such as temperatures or mechanical load changes. These factors allow standard designs to be dimensioned in a way that prevent overloads. More complex situations can be calculated using a variety of methods, from simple calculations to sophisticated simulations.
The behavior of elastic bonding is only slightly influenced by the direction of the force introduction. The reason for this is that stresses are evenly distributed over the adhesive surface. Forces introducing peel loads should be avoided but are less critical than with rigid adhesives. This allows joint designs that would not be safe with other adhesive technologies, for example L-shape joints.

6.5.2 CURING SPEED

Since 1-component products cure by air humidity, the size of the adhesive layer has an influence on the time required for complete curing. Curing means the chemical crosslinking that forms a durable polymer. In a standard climate of 23 °C and 50 % relative humidity, polyurethane adhesive joints with a width of 20 mm need about 2 weeks for this process. Different humidity or temperature levels will affect the curing time.

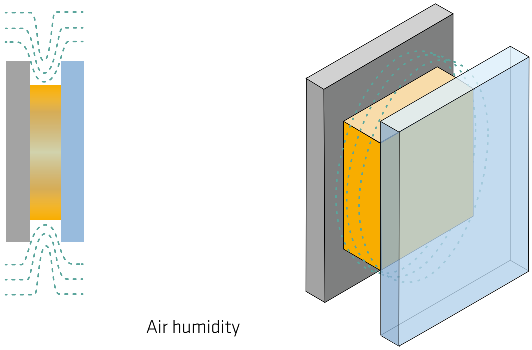


Fig. 6.6 1-component products cure with air humidity

Wider joints also cure, but the time to complete the curing becomes disproportionately longer. Very wide joints are more prone to blistering caused by by-products (e.g. carbon dioxide for polyurethane) released during the curing process. In such situations, it is recommended to use a system that cures regardless of humidity and joint size, for example, Sika® Booster accelerator system or a 2-component system.

6.5.3 ACCESSIBILITY

The dimensions of the joint should be sufficient not only for the engineer making the calculations, but also for the production line and the aftermarket service organization to inspect and perform any necessary maintenance.
Adhesives and sealants joints must therefore be designed in such a way that they are sufficiently wide and accessible to allow cutting tools to be inserted if a bonded part needs to be repaired or replaced, such as in the case of accident repair.
External joints, so called open joints, must be inspected regularly for damage such as delamination, cracks, wear from cleaning agents or any mechanical damage. So they need to be easily accessible.

6.5.4 FUNCTION

Adhesives are made to hold parts together and sealants are used to close gaps. Elastic adhesives can be applied in such a way that the adhesive joint simultaneously bonds and seals, thereby avoiding an additional sealing step. Care must be taken that the product used is suitable for this purpose, for example, it shall be sufficiently weather resistant in case the joint is exposed to sunlight.

6.5.5 SUBSTRATE TOLERANCES

Components such as bus roofs or facade elements are subject to a certain deviation in dimensions and shape. This often leaves relatively large gaps between parts to be assembled. Elastic sealants and adhesives can compensate for such tolerances if they are on the plus side of the tolerance. When on the minus side, it is important that a certain minimum layer of thickness is not undershot. While several millimeters of added thickness do no harm, a few millimeters too thin can lead to a loss of the needed elasticity. In the worst case, this can lead to adhesive break, adhesion loss, delamination of coatings or the fracture of a component.

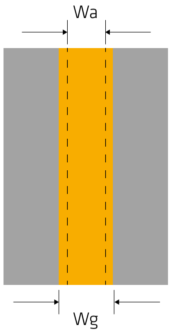


Fig. 6.7
Planned ideal joint:
$\boldsymbol{w_g}$: Planned gap
$\boldsymbol{W_a}$: Minimum joint thickness

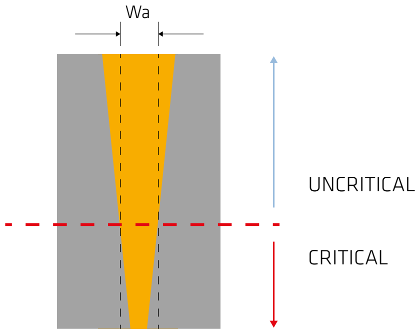


Fig. 6.8
Actual situation:
The actual tolerances must not undershoot the minimum adhesive $\boldsymbol{W_a}$

Tolerances for gaps between parts in drawings shall be such that the minimum allowed value is equal or higher than the lowest required adhesive thickness. The use of spacers can help detect and prevent too small gaps when the parts are assembled.

6.6. MANUFACTURING PROCESS

To achieve the highest efficiency and quality, adhesive and process must be harmonized. To find the right product, a thorough analysis of the current or planned process is crucial. Key aspects to evaluate include:

- Ambient conditions: The temperature and humidity
- Open time: The time needed or available to assemble
- Handling time: The waiting time until the assembled parts can be moved

6.6.1. ADHESIVE VOLUMES

Adhesives and sealants are available in different packaging sizes from around 300 to 600 milliliter cartridges or unipacks, also known as sausages, and in drums up to 200 liters. This will be described in more detail in a later chapter, but here is a short description about packaging, in so much as it relates to applied adhesive volume.
Cartridges and unipacks can be applied with hand dispensers. The volume of one packaging is sufficient for applications like replacement of automobile windshields. The small size and weight makes such packaging handy to reach tight corners and gaps. For larger applications, like adhesive bonding of roofs, large panels or front masks, adhesives are dispensed and applied by pumps out of drums. With such solutions, large gaps can be filled without the need to change the packaging too often. If an application starts out with small packaging but will later gain in volume, it must first be verified that the product selected is also available in the larger packaging sizes.

Elastic adhesive volumes can be calculated from the bead shape, size and length. Beads are usually best applied in a triangular shape to achieve optimum contact and compression behavior. Very stable elastic polyurethane adhesives can be applied in 30 millimeter high beads with a base of 20 millimeters, which is sufficient for a joint 15 millimeters high and 20 millimeters wide.

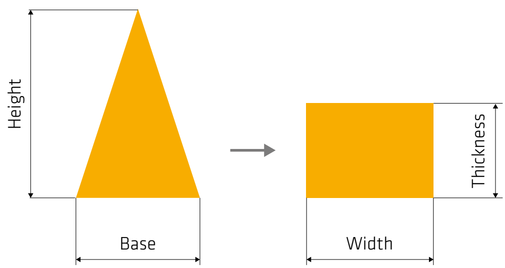


Fig. 6.9 Bead shape and final bead dimension (schematic example)

In the above case, a unipack of 600 milliliter volume would be sufficient for only 2 meters of such a joint. From a 23-liter pail, 77 meters of bond line would be possible. It is therefore advisable to plan for a product that is available in the package that allows efficient application of the desired volumes. The table below illustrates the same for further bead dimensions.

Unipac 600 milliliter					
	Bead width [mm]				
Thickness [mm]	5	10	15	20	25
3	40	20	13	10	8
5	24	12	8	6	5
10	12	6	4	3	2
20	6	3	2	2	1

Pail 23 liter					
	Bead width [mm]				
Thickness [mm]	5	10	15	20	25
3	1533	767	511	383	307
5	920	460	307	230	184
10	460	230	153	115	92
20	230	115	77	58	46

Fig. 6.10
Examples of maximum bead length per package in meter [m]

6.6.2. WORKFLOW

Adhesives, sealants, and pretreatment agents are chemically reactive substances and must therefore be processed within a specific process window. A well coordinated workflow ensures efficiency and quality. So it is advisable to coordinate the selection of adhesives and process planning well in advance. Consideration must be given to drying times and open times, which play an important role in the quality of the bond. Adhesives for manual application usually have relatively wide process windows, partly to allow for process variations that must be expected. By contrast, automated bonding stations can work with faster adhesives that are more controlled by the automation, making short cycle times possible. Selecting an adhesive with the right process window supports a successful and efficient bonding workflow.

6.7. SERVICE LIFE CONDITIONS

The conditions under which adhesive or sealant are used are very important. They have a direct influence on the service life of the joints. The better operating conditions are known, the better it is possible to make the product choice and design in such a way that the expected life span can be achieved without significant maintenance.

6.7.1. CORROSION

The lifetime of the bond or seal depends on many factors, including substrates and processing. Substrates or processes prone to corrosion, from such as salt or chemicals, can cause the bond line to be infiltrated. When selecting adhesives and substrates, it is therefore important to ensure that the entire adhesive bond meets design expectations with regards to corrosion.

6.7.2. TEMPERATURES

Adhesives are polymers and, with that, are subjected to degradation by excessively high temperatures. The higher temperatures are and the longer the exposure is, the higher the degree of degradation. If a product is used to seal the roof top of a vehicles, it is likely to see higher temperatures than the product used for the floor. The correct choice of product and design makes sure that lifetime expectations can be met.

6.7.3. SUNLIGHT

Similar to temperatures, sunlight can cause adhesive and sealants to degrade over time. Visible surfaces can crack or discolor. With transparent substrates, sunlight can destroy adhesion to the substrate within a short time if no measures are taken to prevent it.

6.7.4. CHEMICALS

Aggressive foreign substances may come into regular contact with adhesives and sealants, for example vehicle cleaners, facade cleaners or fuels. Depending on the type of expected exposures, the bond line can be protected from damage by, for example, an additional seal with a suitable sealant used to shield the actual bond against the medium. Special adhesives and sealants are available for known exposures such as rail vehicle cleaners. In any case, it is necessary to clarify the situation with the supplier, who can support with advice in determining the optimum matching of cleaner, adhesive and construction.

6.8. SERVICE AND MAINTENANCE

It is advisable to establish periodic service checks to ensure bonded joints are performing according to the design expectation and to implement maintenance or corrective work. In such cases, or when components have to be replaced, this can often be done quite simply.

6.8.1. REPAIR

Elastic sealing and adhesive joints can be separated and rejoined simply and easily. This can be important for components that have to be replaceable, such as windshields. It is sufficient to cut out the old windshield with a sharp blade or a special wire. The new bonding can then be carried out directly on the existing residual, fresh cut and clean bead.

This easy repair process has led to the existence of two variants of many products, one for original equipment and one for the repair aftermarket. The original equipment product has processing properties that are ideal for efficient factory production, such as very short crosslinking times. Products for the aftermarket are set to perform well under repair conditions, which in the extreme case is that of mobile roadside windshield replacement. If the original equipment and repair case are known at an early stage, the products can be ideally matched.

6.8.2. RECYCLING

Cured adhesives can be disposed of in accordance with national regulations. If necessary, adhesive beads can be mechanically separated from the substrate. Since elastic adhesives and sealants are relatively soft, they can be easily separated from the substrate with a blade or a sharp scraper. The easier the access to the connection, the easier the process is.

7 ELASTIC BONDING IN PRACTICE

BEST PRACTICES ARE USED AS INDUSTRY BENCHMARKS TO SHARE PRACTICES, METHODOLOGY AND SOLUTIONS THAT HAVE LED TO SUCCESS IN OTHER INDUSTRIES AND APPLICATIONS. They show how real life businesses have managed projects to ensure plans are made and resources used to the fullest, utilizing the latest technologies and techniques.

7.1. TRANSPORTATION

City of Zurich tramcars is a best demonstrated practice benchmark of modern commercial vehicle engineering utilizing elastic bonding technology. The newly designed Cobra articulated tram was to be the first low floor system to operate on the local tram network and is now used on most lines, alongside other tram models.

The project design team was given a brief with three focus areas, comprising five goals. The first focus area was modernity, the design must be innovative with contemporary aesthetics, it simply had to look good. Second was in the area of performance where three goals were set. The first and most important being low floor construction, together with low overall weight and low cabin noise levels. Finally was manufacturing efficiency, production of the tramcars had to be low unit cost.

In order to meet these requirements, the designers made evaluations of current products and processes to see where improvements could be made. They then set about developing a new modular hybrid construction system where a series of prefabricated and finish lacquered modules including driver's cab, sidewall panels, windshield, roof and floor sandwich panels, would be adhesively bonded to the aluminum body of the car.

Fig. 7.1
Adhesively bonded windshield

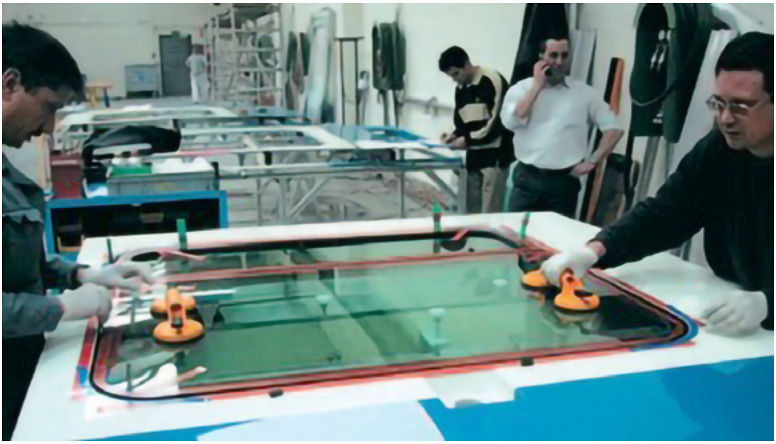


Fig. 7.2
Installation of window glass in sidewall panel

MODULE	SUBSTRATE MATERIAL	ADHESIVE
Driver's cab	Glass fiber reinforced plastic (GRP) Laminated safety glass (LSG)	Cure-accelerated 1-component polyurethane adhesive (Booster) 1-component polyurethane adhesive
Sidewall panels	GRP/Toughened safety glass (TSG)	1-component polyurethane adhesive
Roof sandwich panels	Aluminum, primed	1-component polyurethane adhesive
Floor sandwich panels	Aluminum, primed	1-component polyurethane adhesive

Fig. 7.3
The most important defined elastic adhesive applications

The use of elastic bonding technology in the form of boosted and non-boosted 1-component polyurethane adhesives enabled the design and engineering team to meet all of the set goals. Realizing its vision for a hybrid low floor tramcar, designed and manufactured in an efficient and cost effective production process. The potential benefits of elastic bonding described in earlier sections of this book played a pivotal role in this case, namely:

- Bonding and sealing could be completed in a single operation
- Joining of different materials and different types of surface finish, such as full paint system, primer coat, etc. was possible
- The adhesives had the ability to accommodate manufacturing tolerances due to their gap filling properties
- The bonding operation was distortion free with no mark through, requiring no further refinishing
- The elastic bonded joints facilitated a uniform distribution of stresses under heavy loading
- Excellent damping and improved ride comfort were attained due to the adhesive elasticity properties

In the planning and development work, attention was also focused on optimizing the stiffness and strength of the structure. Computer based FEM techniques, as previously noted, were used to calculate shear, compressive and tensile stresses under a variety of load conditions. The decoupled spring elements were factored into the calculation as the spring constant for the adhesive joint, which is directly dependent on the area of the bond face and the thickness of the adhesive layer. In vehicles such as this one, which are built using hybrid construction methods, the dimensioning of the adhesive joints is given a high priority at the earliest development stage, since this is critical to attain the necessary design strength.

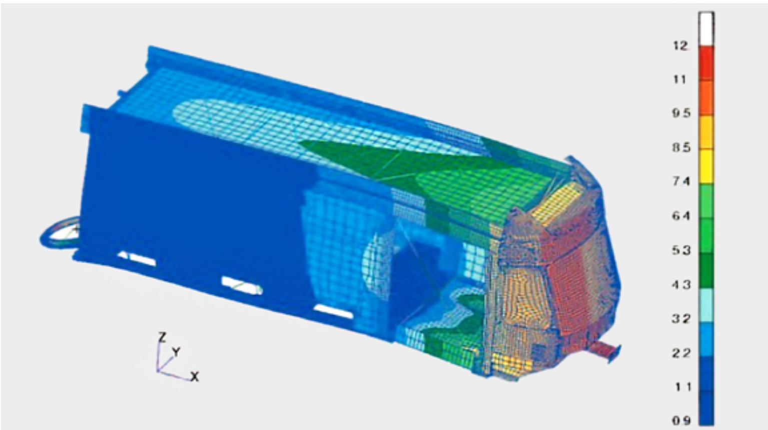


Fig. 7.4
Using FEM simulation to model global deformation in the tramcar when cornering

7.2. ELECTRIC CITY BUSSES

Following the global trend of manufacturing green powered buses, a leading North African manufacturer of buses and coaches launched its fully electric city bus, that participated in COP27 in Sharm El-Sheikh November 2022. Contributing towards the vision to reduce greenhouse gases, these city buses now serve major city public transportations.

Fig. 7.5
Bonded windows and panels

The company needed sustainable adhesive solutions for their EV bus that also provided performance benefits, durability and safety. Passenger comfort was to be enhanced by utilizing the vibration and sound dampening qualities of elastic adhesive. In addition, the modern bus design required other adhesive solutions including larger side windows direct glazing and adhesive sealant with low odor and non-corrosive qualities.

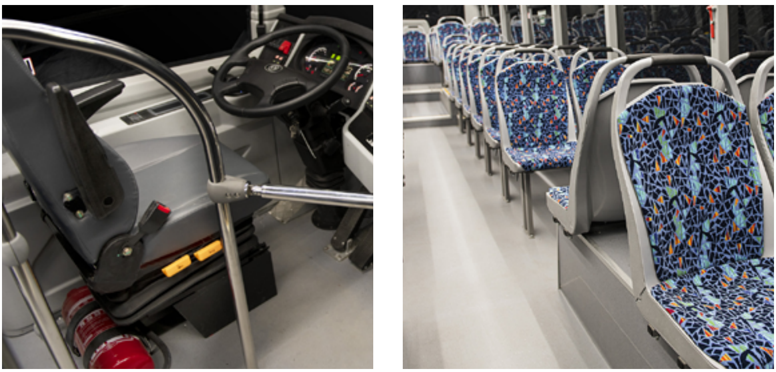


Fig. 7.6
Sealed floors

Fig. 7.7
Various bonding and sealing applications

The requirements to build the EV city bus were exactly met using a range of Sikaflex technology systems including Sikaflex®-252 elastic adhesive for vehicle assembly bonding with vibration and sound damping capabilities, something we explained in earlier sections of the handbook. Sikaflex®-263 direct-glazing elastic adhesive with good ageing and weathering resistance and Sikaflex®-221 multi-purpose adhesive sealant with low odor and non-corrosive properties complimented the range of solutions.

Fig. 7.8
Used products

APPLICATION	ADHESIVE	ADHESIVE PROPERTIES
Assembly bonding	Sikaflex®-252 elastic 1-component polyurethane	Adhesive with vibration and sound damping capabilities
Direct glazing	Sikaflex®-263 elastic 1-component polyurethane	Adhesive with good ageing and weathering resistance
Multi-purpose	Sikaflex®-221 elastic 1-component polyurethane	Adhesive sealant with low odour and non-corrosive properties

Elastic bonding properties are evident in this case for fully electric city bus bonding:

- The elastic adhesive Sikaflex®-252 used for assembly bonding helps reduce vibration and noise for passengers and drivers.
- Bonded components avoid the need for drilling, thereby reducing potential corrosion and eliminating the risk of drilling in the proximity of battery packs.
- The elastic adhesive has the ability to accommodate assembly tolerances and gaps where necessary.
- The elastic bonded joints facilitate a uniform distribution of stresses under load.

7.3. VEHICLE RACKING SYSTEMS

A leading European manufacturer of racking solutions for service vehicles, with subsidiaries in Europe and Asia and with a global partner network, serve a worldwide customer base. Their racking systems carry the cargo during transport and need to be firmly fixed to the van's body. This is achieved by mounting the racking onto integrated aluminium rails in the floor panel, which are bonded to the vehicle chassis floor.

The use of elastic bonding demonstrates best practice in this customer case, where mechanical fasteners such as rivets and screws have been replaced with adhesive bonding to adapt to the growing number of electric vehicles in service, where under-floor battery packs prevent drilling for mechanical fixings. In addition, by avoiding mechanical fasteners, loads are more evenly distributed, corrosion risk is decreased and vehicle residual values may be enhanced.

Fig. 7.9
Modular floor system, adhesive bonded

The customers engineering team calculated the adhesive system and joint dimensions requirements by simulating stringent load scenarios for their racking systems and vehicle operation. Only a high-strength polyurethane such as Sikaflex®-268 can meet the strength requirements. The flat, lightweight floor panel is installed on the uneven chassis; the adhesive joints are massive to fill the gaps. Hence, curing the adhesive would take significant time. Here the Sikaflex® Booster technology facilitates fast through-curing, allowing the vans to be put into operation soon after assembly.

LOCATION	ADHESIVE	USE CASES
Smaller service centers	Sikaflex®-268 PowerCure Cure-accelerated 1-component polyurethane adhesive technology	Flexibility for smaller volumes
Larger service centers	Sikaflex®-268 Booster technology Cure-accelerated 1-component polyurethane adhesive	Bulk application volumes

Fig. 7.10
Used products

Sika's system approach for Sikaflex® Booster adhesive allows scaling of the bonding process to suit the various customers service centres without re-engineering the design of the van conversion kit. In smaller service centers, Sikaflex®-268 PowerCure provides the optimal solution; while in larger centers, Sikaflex®-268 Booster is applied in bulk allowing cost improvements while maintaining the same adhesive high performance.

We interviewed a senior manager to find out more:

How did you tackle the design challenges that go along with the vehicles' use cases and loads on your racking system?
We have done both FEM simulations and physical tests to resist harsh brakes and crash forces. The FEM simulations have been done for individual attachments such as complete racking in a vehicle body. Both physical load capacity tests and full-scale crash tests have been conducted.

How does Sika's System approach, along with the Sikaflex® Booster Technology, help you optimize your production?
It allows scaling the process, for example by using bulk instead of PowerCure for larger jobs or sites. The handling of a glue machine with bulk packages could be challenging especially in smaller workshops, where a glue gun is preferred for flexibility. The bulk package saves cost for larger workshops with larger amount of glue used.

How well did the transition from traditional fasteners to adhesive bonding meet your targets?
We promote a non-intrusive solution, especially when there are issues with drilling, as for example with electric vehicles. The non-intrusive installation is more expensive in the short term, but avoiding problems in the workshop will pay off in the long run. In vehicles where it is difficult for ordinary drilling/bolting, glued fixation points could solve the problem.

The use of elastic bonding technology in the form of Sikaflex®-268 Booster and Sikaflex®-268 PowerCure helped achieve the required technical performance goal by providing a high strength fixation of the racking systems, meeting the needed strength for safe operation, whilst avoiding mechanical fixings. And achieve its versatility and costs effectiveness goals by having one global fast curing elastic adhesive system solution that ensures vehicles are ready to operate quickly.

The performance advantages of elastic bonding are well demonstrated in this case for a bonded commercial vehicle racking system:

- The bonded floor rails avoided drilling where battery packs are located
- Avoiding drilling also reduced the risk of corrosion
- The adhesives had the ability to accommodate large gaps on uneven floor profiles
- Sikaflex®-268 polyurethane adhesive was able to meet the demanded high strength
- The elastic bonded joints facilitated a uniform distribution of stresses under load
- Sikaflex® Booster Technology ensured fast adhesive curing, whilst maintaining adequate working time and could be interchanged with corresponding 1-component polyurethane as a system solution

7.4. BUILDINGS

In the field of buildings and architecture, a best practice benchmark case of elastic bonding was demonstrated by a development project in the window industry. A leading PVC profile window manufacturer had previously been obliged to use steel reinforcements within the profile for strength and wanted to create a lightweight, slim PVC profile window system with equivalent strength and larger glass area, but avoiding steel inserts. The project also defined that the production process should be streamlined with higher efficiency compared to the current manufacturing process.
The idea was to use the stiffness of the glass to contribute to the strength and rigidity of the construction by utilizing elastic adhesive technology.
In order to make the stiffness of the glass contribute to the overall strength of the window assembly, similar to direct glazing in the automotive industry, a new window system with elastic adhesive was developed.
The result was a slim profile PVC window sash that was able to dispense with the usual steel reinforcement. The designer's goals were achieved by using a warm applied adhesive that is injected into the narrow gap between frame and sealed glazing unit.

Fig. 7.11
Sealed unit and sash profile joint detail

By injecting the adhesive with a 0.5 mm diameter fine nozzle under a high pressure of 200 bar, the sash frame and the edge of the glazing unit effectively became a single structural assembly. When the adhesive cools down, it quickly attains sufficient handling strength for the production process to continue without delay.
An adhesion promoter was integrated into the extruded section of the PVC profile, so that the entire manufacturing process could be largely automated. This design and production process resulted in a window system that fulfilled the goals and offered many advantages to the manufacturer, and importantly, also to the end user:

- The manufacturing process could be automated
- A reduced window weight created savings in raw materials
- The new design glazing unit acquired improved thermal properties
- The end user could receive units with larger visible glass area and modern styling
- A stiffer sash assembly resisted twisting and racking and was easier to open and close
- Security was enhanced because the system now had greater resistance to burglary attempts

8 ADHESIVE APPLICATION, EQUIPMENT AND PROCESSES

ADHESIVE APPLICATION IS THE PROCESS OF BRINGING THE ADHESIVE OR SEALANT FROM ITS PACKAGING TO THE POINT OF USE, usually onto one of the two parts to be bonded together. 1-component adhesives do not need to be mixed, but they must be stored in airtight containers. 2-component adhesives need to be mixed by means of static or dynamic mixers. A suitable application tool is required in either case.

8.1. ADHESIVE FEEDSTOCK PACKAGING

1-component elastic adhesives and sealants are usually packed in cartridges, unipacks, pails or drums. Unipacks are also known as sausages and pails are small type of drums, sometimes called hobbock.

The most common application tools for lower volumes are cartridge or unipack dispensers. For higher volumes, drum or pail pumps are used. These devices (dispensers) and equipment (pumps and metering units) will be explained further below.

			
	CARTRIDGE	**UNIPACK**	**PAIL AND DRUM**
Volumes	300 to 310 milliliter	70 to 600 milliliter	20/23 liter to 195 liter
Application tool	Cartridge dispenser	Unipack dispenser	Pumps

Fig. 8.1
Typical packaging

8.1.1 CARTRIDGES AND UNIPACKS

Cartridges and unipacks are easy to use and are the most common packaging for single use of small quantities of adhesive. Cartridges are made of aluminum, plastic or composite materials that are resistant to accidental damage and easy to store. Processing is possible with a variety of commercially available application dispensers. For the production of unipacks, adhesives are filled into thin composite films made of aluminum and plastic. The application of products in unipacks is carried out with similar dispensers as for cartridges. Empty unipacks leave a smaller amount of residual waste compared to cartridges.

8.1.2 DRUMS

200 liters drums are most commonly used for viscous products in large quantities. They have an inner diameter of 571.5 mm and mostly have an inliner. Being made of thin steel they are susceptible to damage and must be handled with care. The waste of such a packaging is less than 5 % if the equipment is optimized and if a support plate is provided to avoid the bottom of the drum bending. This packaging needs to be handled by drum lifts or similar due to their weight when full.

8.1.3 PAILS

Pails are “small drums” with volumes between 20 and 50 liters. 20 and 23 l pails are common, and a wide variety of products are offered in this packaging. They are available in 280 mm and 284 mm diameter. In contrast to the smaller pails are the 50 liter pails used for a limited range of products. They come in 360 mm and 365 mm diameter and are mainly used in the automotive industry. The pumping equipment for pails is relatively simple and easy to handle.

8.2. APPLICATION OF ADHESIVES

8.2.1 1-COMPONENT MANUAL APPLICATION BY CAULKING DISPENSER

Cartridges or unipacks are commonly used for low volume applications which require high mobility and where access is tight. The operator simply carries the cartridge dispenser to the point where the application takes place.
Manually, electrically, or pneumatically driven dispensing tools are used depending on the adhesive or sealant viscosity and the frequency of use. For example relatively low viscous sealants used in small volumes can be applied with a manual dispenser.
Battery and pneumatic dispensers, using carry-on air tanks, provide power for remote applications without supply lines.

Fig. 8.2
Manual application

Manual dispenser		
Powered manual dispenser		

Fig. 8.3
Manual application tools

8.2.2 MANUAL 2-COMPONENT CARTRIDGE DISPENSERS

The cartridge application criteria for 1-component products also generally applies to 2-component dispensers. However, manual application of small, short beads using a 2-component cartridge usually leads to fluctuating material quality. The start and stop of flow negatively influences mixing quality. Hence, the more continuously a 2-component cartridge is extruded, the better the mixing quality. As a consequence, it is recommended to use battery or air driven 2-component dispensers in order to ensure a smooth and continuous adhesive flow.

8.2.3 SIKA POWERCURE® DISPENSER

The PowerCure® dispenser is a unique applicator for adhesives that are compatible with Sikaflex® and Sikasil Booster technology. It combines the ease of use of a battery driven 1-component type dispense system with the advantage of a fast curing 2-component system. The dispenser can be loaded with unipacks containing an additional small booster cartridge alongside and has a built in dynamic mixer drive for optimal mobility.

Fig. 8.4
PowerCure dispenser and material package

8.2.4 MANUAL APPLICATION BY PUMP EQUIPMENT

When the volume for one, or just a few, applications is higher than the content of a cartridge or unipack, most users switch to manual application out of pumps. This reduces the frequency of packaging changes and, since the output is higher with a pump, the process time is faster. A drawback of pump stations is the need to have hoses from pump to nozzle and limited reach if the pump is not mobile. If the point of application is at a fixed position in the workshop, a static installation using balance arm makes for easier handling of the heavier application equipment.

Fig. 8.5
Bulk dispenser with pump for booster products

If faster extrusion is required, or the material quantity to be applied per part or per day is high, commercially available pump equipment for 23 liters pails or 200 liters drums are available for 2-component or Booster systems. The equipment has an application valve attached.

Fig. 8.6
Bulk dispenser with pump for 1-component products

8.2.5 SEMI-AUTOMATED APPLICATION BY CARTESIAN ROBOTS

Semi-automatic equipment is the choice when it comes to round beads applied on small parts. If numerous similar parts must be produced with repetitive accuracy, most users go for a cartesian robot carrying a cartridge dispenser on the Z-axis or moving a nozzle, fead from a small pump equipment. This kind of application offers application precision combined with modest investments.

Fig. 8.7
Cartesian robot

Benchtop dispensers are most common for small, repetitive and precise applications. These machines can be programmed easily and offer a broad application of round beads on various substrates. Alternatively, cartridge dispensers can be moved by the benchtop machine or a collaborative robot, known as cobot.

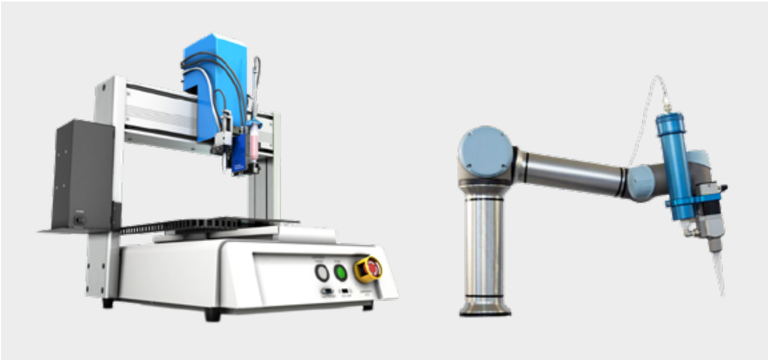


Fig. 8.8
Benchtop dispenser and cobot using cartridge supply

8.2.6 FULLY AUTOMATED APPLICATIONS USING ROBOTS AND DISPENSERS

Fully automated dispense equipment must be used for application on large parts with a need for highly accurate dispensing and precise path control, and for multiple work shifts on assembly lines. This is especially true for triangular bead application, because the application head needs to be rotated around its axis to orientate the bead profile.

Such dispensing systems include a supply pump, or two for uninterrupted material supply, a dispense unit and a robot. During planning, it must be decided whether the robot moves the bonding part (fixed nozzle application) or the outlet valve with nozzle. Both are possible but must be determined at an early stage.

Fixed nozzle application utilizes one robot for pick up, application and installation. It's called fixed nozzle setup because the robot moves the part along a fixed nozzle for the application. Moving nozzle application uses one robot to apply the adhesives and another for pick up and installation. This is called moving nozzle setup because the robot moves the nozzle along the bond line on the fixed part. The installation can of course also be done manually.

Fig. 8.9
Automated dispense equipment

Depending on whether the material to be processed is a 1-, 2-component or a Booster product, the setup plays an important role in the achievable precision of the application. Long hoses delay and accumulate flow, which can lead to mixing ratio fluctuations or bead size variations. If high precision in dispensing, bead size and mixing is required, a constant application speed with a well balanced dispenser setup is crucial.

Fig. 8.10
Glazing station of an automotive OEM

8.2.7 AUTOMATION OF A MANUAL PROCESS

Do not underestimate the ability of process operators to compensate for unexpected or unplanned variations in production materials or process. For instance, an operator can easily adapt to a flow change of a pump, or the dispenser can quickly be moved to the correct position or around obstacles without any problem and you will not detect any of these issues in the final product.
It is important, when considering automating a manual bonding process, to

understand that a robotic applied bead is repetitive and does not adapt to tolerances or unpredictable obstacles or similar. Neither does a robot system compensate for changing flow behavior or material interruption unless sensor systems are in place to do so.
Therefore, it is not recommended to simply attach a manual pump systems outlet dispenser on a robot. Instead, a dosing or dispensing unit shall be used. Automating a process requires thorough planning and considering important requirements in order to succeed with such a transformation.

Taking care of the following topics supports a successful plan for automation of a bonding process:

TOPIC	CONSIDERATIONS
Volume stream	Bead size and application speed defines the required flow of the dispensing system. Or in other words, bead length, bead volume and application time available defines both application speed and material flow.
Minimum supply flow	Material consumption per part and remaining cycle time for filling the dispenser defines the minimum supply flow requirement.
Geometry	Part alignment and proper position check of the part ensures the bead is on the right spot with the correct shape.
Fixation	Mostly, part fixation, or put-in-position, is sufficient to ensure correct placement when using suitable adhesives.
Tolerance detection	To cope with tolerances, optical and mechanical measurement of the part deviation along all three dimensional axes is very helpful. Note that implementation of such technologies requires professional setup and specific skills to implement on a robot cell.
Flow and speed	Flow measurement or adaptation of flow according to robot speed. Note: Ensure the flow is capable to feed or follow the robot's application speed.
Smooth motion	Smooth motion of the robot during application, always try to keep a constant application speed.

Bead closing	Concept for a proper closing section of the start and stop of a bead ensures tightness when bonded.
Cycle times	A good understanding of the entire assembly process is important to determine the required cycle time for the bonding process. It is recommended to involve the adhesive supplier and the equipment supplier in this step at an early stage. Adhesive supplier can support with experience on the behavior of the products in an automated process.
Hose diameter and length	Material supply length affects the supply flow rate. Thus, the supply hose diameter and length must be adapted to meet the supply flow requirements and provide some reserve.
Robot pro-gramming	If the robot is to react to external variables or sensor signals, very profound robot programming knowledge is necessary. This expertise is often only available from suppliers of complete bonding cells, such as for the automotive sector.

Fig. 8.11 Automation considerations

In summary, coordination of the production process, processing equipment and adhesive selection must be addressed early and together in order to arrive at the ideal solution.

8.3. PROCESSING

Adhesives are usually shear sensitive, which means that some application properties, such as non-sag and cut-off string, may be negatively influenced. If adhesives are heavily sheared, they may lose their ability to prevent a bonded part from sliding down, due to gravity. The cut-off string may also increase and contaminate the substrate at the end of the adhesive application. This is especially critical if adhesive needs to be applied on parts with high visual contrast, such as black adhesive on a white car body.

There are also non-visual aspects influenced by shear, like viscosity, pressure or flow rates. These parameters become crucial on automated dispensing systems that check pressure values for maximum and minimum values. It might become necessary to adjust parameter settings if viscosity changes due to shear.

1-component polyurethane based adhesives show a specific behavior named “non-Newtonian fluid behavior”. This means that their viscosity is related to many parameters and these parameters influence themselves within equipment. For example, viscosity is related to temperature. When products are pumped, there is friction. I.e. shear resistance, which increases the temperature of the product. The higher temperature lowers viscosity, resulting in less friction, but also changing properties like sagging or lower compression resistance. A thor-

ough understanding of these principles and sound practical experience is needed to deal with this interrelated behavior.
To avoid problems arising from the above, each adhesive must be processed in such a way that excessive shear is avoided. Together with the choice of the right adhesive, the choice of pumping technology and processing parameters also play an important role. Therefore, it is advantageous if the adhesive manufacturer and equipment supplier have experience in how their respective systems work together.

8.4. BEAD TYPES

Adhesives can be applied in different geometries. The main types are triangular and round bead.

8.4.1 ROUND BEAD

Round beads are useful for gasket application or general bonding of flat parts. Since application of a perfectly round bead is not possible, the bead becomes oval, having flat top and bottom. The advantages of a round bead are the simple application method and there is no need for a rotating nozzle. The disadvantages of round beads are potential for air entrapment and limited ability to wet surfaces and compensate for tolerances.

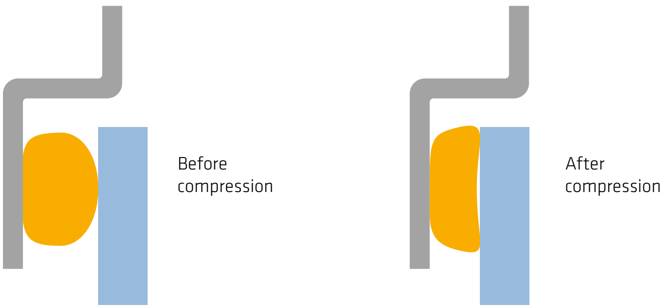
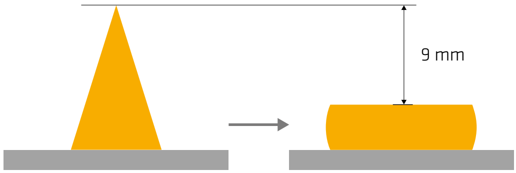


Fig. 8.12 Visualization of a round bead showing air entrapment after compression (schematic)

8.4.2 TRIANGULAR BEAD

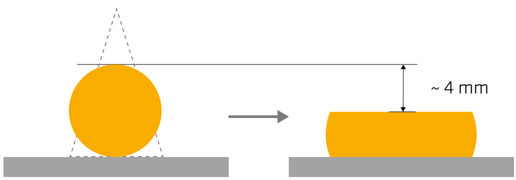
Using a triangular bead has proven to be the best solution for an accurate result. It avoids air pockets and compensates for large construction tolerances, which is important for correct wetting and bonding dimensions. Be aware that applying a perfect triangular bead by hand requires practice.
To illustrate, a triangular bead with a base of 8 mm and a height 13 mm, can potentialy overcome tolerances up to 9 mm if compressed to 4 mm.

Fig. 8.13
Compression distance of triangular bead



In contrast to the triangular bead above can a round bead (same volume) overcome a tolerance of 4 mm only.

Fig. 8.14
Compression distance of round bead



The higher compression distance with the triangular bead is extremely helpful to cover production tolerances of parts. The progressive increase in compression force allows accurate positioning of the components to be bonded.
As can be seen in the below illustration, an advantage is gained by applying the triangular bead with a lateral motion and with the nozzle in contact with the surface. This provides a perfect wetting of the surface to which the adhesive is applied.
This method of application also gives a repeatable and stable bead size, which is important for any unattended automated application.

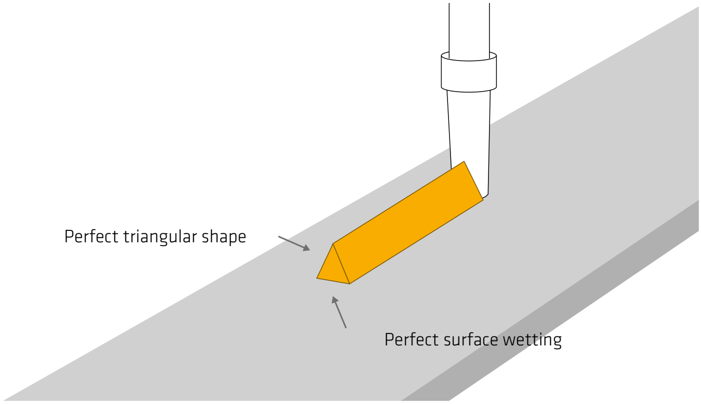


Fig. 8.15
Perfectly applied triangular bead

From an application perspective, the triangular bead has the drawback that a rotating nozzle is necessary to orient the triangular shaped outlet during application and surface contact is required to create a perfect triangular shape.

8.4.3 DRY BONDING

Dry bonding is the process of filling a gap from the outside of the joint. Special care must be taken to avoid air entrapment when filling large gaps within a closed joint.
The normal process comprises pretreatment of the bonding surfaces followed by positioning of components. A foam profile or a spacer tape is used to limit the joint depth and the adhesive is injected whilst ensuring proper surface wetting and avoiding cavities.
It should be noted that certain criteria must be respected. Pre-treated surfaces must not be touched or contaminated prior the adhesive application. Pay due attention to the maximum open time of pretreatments and use spacers to ensure correct joint dimensions.

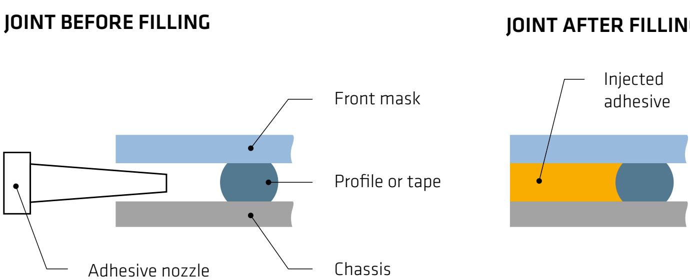


Fig. 8.16
Joint before and after filling

For such applications special nozzles might be necessary. With the advent of 3D-printers, it is now possible to print nozzles that fit gaps and displace air perfectly.

Fig. 8.17
Example train front mask

As dry bonding is mostly used in combination with large joint dimensions, it may be necessary to use a product that cures independently of air humidity, for example a solution with Sikaflex® Booster or a 2-component product.

8.4.4 SURFACE APPLICATION

Some sealants are designed for large surface application by spray dispensers, which are available for both cartridge and unipack packaging.

Fig. 8.18
Example spray application

As a cautionary note, spray application creates a risk of exposure to spray mist and splashes of products. It is therefore very important to perform such applications using correct personal protective equipment only. For further details consult allways the most actual safety data sheet.

8.5. PUMP SYSTEM TIPS

8.5.1 MATERIAL PUMPABILITY

Fluctuating ambient temperatures can become a challenge for pumping high viscous material. Extrusion rates might be too low under cold ambient temperature. In the worst case, air intrusion into the material can happen due to insufficient RAM-force for feeding too cold material to the material lower pump. Best results are achieved if the equipment with product is kept at a constant temperature within the optimum temperature range as described in the product data sheet.

8.5.2 AIR ENTRAPMENT

Flushing a pump system after changing a drum is a must to ensure an air free application. This is even more important on automated production lines without human inspection of the bead. Check the equipment manual for how to perform a de-aeration or flushing. Ask equipment supplier for proper documentation and training.

8.5.3 PUMP PERFORMANCE

By carefully watching the material pump piston movement, the functionality of a chop and check material pump can be identified. The rod between air motor and material pump shall move with the same speed in both stroke directions. If the rod moves faster in one stroke direction, or partially moves faster during one stroke, there is a high chance of malfunctioning valves inside the material pump. In this case, check material flow at the purge valve of the material pump. Both strokes must provide a constant material flow without air or interruption. A proper function of the material pump is very important when the material pump is also the metering unit.

8.5.4 SHOT METERS - PISTON DOSING UNITS

The most important reason to use a piston dosing unit close to the outlet is, that due to the short distance to nozzle, it provides a high and precise flow during application and can be refilled with much slower flow rate. One benefit is that a less powerful supply pump can be chosen to fill the dosing unit. The second reason to use a piston dosing unit is the low shear of the material due to its mechanical design. Piston dosing units usually come with a sophisticated control allowing adjustment of pre-pressures and other parameters.

If a high material quantity is necessary, piston dosing unit can be arranged as a double acting system. With this setup, one dosing unit is filled while the other is applying. The drawback is the need for a supply flow rate higher than the outlet flow rate to fill the second dosing unit in due time. Hence, the supply hose length will undergo the same limitations as when feeding a gear meter.

8.5.5 CONTINOUS DISPENSER - GEAR METER

If endless dispensing or high volume per application is required, gear meters have the advantage of almost endless dispensing capability. Gear meters operate optimally if the inlet pressure is the same as the outlet pressure. Importantly, the flow from the supply pump must be the same or slightly higher than that of the outlet of the gear meter. This means that the hose length between supply pump and gear meter is limited to guarantee an adequate feed to the gear meter.

The shear rate is higher as for piston dispenser and pre-pressure adjustments are usually not available which makes an adhesive start on-the-fly very challenging. Screw spindles or progressive cavity pumps offer similar options as gear meters, albeit their pressure level may be lower. Some of them have better accuracy or lower shear than gear meters. Sometimes filler or material properties prescribe or exclude certain metering principles.

In order to overcome seasonal changes or batch related differences it is recommended to be able to adjust the following settings at any time:

8.5.6 ADJUSTABLE SETTINGS ON PUMP/ DISPENSE SYSTEMS

SETTING	DESCRIPTION
RAM-Pressure	To adjust follower plate pressure in case of viscosity changes or temperature variations.
Pump motor pressure	In order to allow adjustments of the filling of a dosing unit or feeding of a gear meter, or to adapt extrusion flow for manual application. Having the ability to adjust this pressure ensures filling a dosing unit within the cycle time even though viscosity or temperature influences the flow. Bear in mind that it is not recommended to adapt the flow without taking care of pressure settling in case of a 2-component machine. Some machine types react with severe mixing ratio issues in case of flow changes as they are intended to be used with constant and unchanged flow. In the latter case a proper flushing needs to be performed to adjust the system pressure to the new flow and the mixing ratio needs to be checked or corrected.
Pre-pressure value	Either the system is capable of adjusting itself to the actual situation, and therefore can cope with viscosity and temperature fluctuations, or it is strongly recommended to regularly check the setting for correctness. For instance daily.
Dosing unit filling time alarm	This can help in case the material flow is lowered due to higher viscosity or lower temperature and therefore the filling time is no longer sufficient. In this case it's better to change pump motor pressure first to ensure filling within the cycle time.
Maximum pressure value	In some cases, mostly seasonal, it is necessary to adjust the maximum pressure value to be able to process material with slightly higher viscosity or aged material at the end of its shelf life. If the changes are higher than 15-20 % there might be an issue with the equipment, or the material has reached a critical stage, such as aging etc. Do such adjustments with caution and don't forget to reset the value if the conditions have changed. I.e. drum change, season change etc.

Fig. 8.19 Settings adjustments

8.5.7 DOSING UNIT PLACEMENT

In automated environments, dispense system setup on robots must be placed according to the flow dynamics basics. State of the art setups show a dosing unit close to the outlet (or directly attached to the nozzle) to eliminate the negative impact of long distance between dosing unit and outlet valve. This is even more important for 2C-adhesive processing.
To control flow rate in due time and simultaneous to the robot speed, dosing unit must be placed as close as possible to the outlet. This is the reason, why it is not recommend dispensing directly from the supply pump. The accuracy and simultaneous response of such a system is delayed, because of the hose between the metering unit and the outlet valve. Even if the supply pump has servo motor control, the delay and the pressure loss can't be outsmarted as it's a matter of physics.

We mention values to be set as adjustable because of the latest developments in responsibility and ownership on automated cells. In order to reduce the risk of maladjustments, several parameters have been limited in their adjustability or even locked to avoid unintended adjustments. This starts to get critical when there are no changes allowed at all. RAM-pressure and pump motor settings are the most sensitive for batch variations, aging and seasonal influences. Blocking the adjustments of these parameters can lead to unnecessarily refused material due to slight variations. In times of sustainability, striving for ecologically meaningful use of material and commercial good sense, it is our belief that certain adjustments necessary for coping with exceptional situations should be allowed and fostered.

8.6. MAINTENANCE

Properly maintained equipment provides the best application quality and ensures a smooth and uninterrupted production. Automated processes without human supervision of applied beads, means maintenance plays an even more important role. The risk of production stops due to broken equipment or parts can be significantly reduced when following the maintenance plan provided by the equipment supplier. Even small things like a gasket or an O-ring can cause a malfunction and stop production. Keeping equipment in good shape is crucial for successful and safe applications.

The less time spent on human monitoring of an application or automated cell, the more important additional tools such as visual or optical in-line inspection and machine alarms such as maximum pressure, mix ratio alarm or volume per part become. These tools are very helpful and sometimes a prerequisite for error free and accurate application.

8.6.1 REGULAR INSPECTION

Regular inspection and quality checks are highly recommended. Material dispensing technologies are subject to wear and tear, therefore are regular checks necessary to ensure material quantity and proper mixing ratio.

Such checks comprise extrusion check programs, where it is evaluated if the equipment dispenses the required amount of product. For 2-component equipment it is mandatory to check the mixing ration, which consists usually of an extrusion check of both components and in addition tensile lap-shear samples to confirm the product properties. Other points to be inspected: pre-pressure, RAM-Pressure and pump pressure (air motor), etc.

9 QUALITY ASSURANCE

A SPECIAL PROCESS IN MANUFACTURING, according to ISO 9001 standards, is described as any process where there is no way to verify the finished product without proving its function through destructive testing. Such processes, which include welding, painting or adhesive bonding, require special care regarding quality control. Accordingly, there is a requirement for constant monitoring or observance of documented processing instructions, or both, in ensuring that the quality objectives are met in accordance with EN ISO 9000.

9.1. INTRODUCTION

An efficient quality management system for all components and processes is one of the key factors for permanent bonding and sealing as well as consistent production. A well balanced quality system can be established through three main phases:

PHASE	PHASE DESCRIPTION
	The first phase starts in the plant of the adhesive manufacturer, where specific quality procedures ensure products are produced consistently.
	The second phase continues where the object to be bonded and sealed is planned. Joints and processes are designed in a way that supports a robust production process and long lasting joints. This phase includes the necessary tests to secure functions such as adhesion under expected service conditions.
	The third phase is when adhesives are applied, and components assembled in the manner specified and planned beforehand.

Fig. 9.1
Three phase process

The following text focuses on the second and especially the third phase. When planning quality management for adhesive bonding, the following must be considered.

Adhesive joints cannot be completely tested non-destructively. This means that the quality of the bonded joints must be ensured during production. There are only limited possibilities to check the quality afterwards without destroying the joint.
All process steps influencing the quality must be identified, understood, described, controlled, and documented, even the processes taking place at suppliers if they can influence the quality of the adhesive bonding.
The identified process variables shall be checked for being measurable to set quality limits. E.g. target volumes, dimensions, temperatures, waiting times etc.
In the quality management it shall be defined how and by whom these processes are monitored and how the results of these considerations are dealt with.
Appropriate quality management prevents failures in the process which, in the worst case, may not be detected until the finished good are in use at the user.
Because bonding process control is so important, this places increased demands on the qualification and training of employees.

9.2. STANDARDS

Guidelines for quality management in the use of adhesives and sealants are available from various sources. These can reinforce the recommendations and process windows to be found in the adhesive supplier's documentation. Different standards allow the user to match the quality metrics to the complexity of the application, which can also include risk assessments.

9.2.1 RAIL INDUSTRY

One of the first standards to establish procedures for quality and safety of adhesive bonding has been DIN 6701. Although made for bonding and sealing on rail stock in Germany, DIN 6701, Parts 1-4, "Adhesive bonding of railway vehicles and parts" contains aspects that are equally useful for other manufacturers. DIN 6701 was the basis for the international ISO/DIN 21368 standard published in 2021.
Other railway related quality control standards are DIN SPEC 2305-3 "Quality requirements for adhesive bonding processes - Part 3: Requirements for the adhesive-technical personnel" and EN 17460 "Railway Application – Rolling stock products – Adhesive bonding of rail vehicles and their components".

9.2.2 GENERAL ASSEMBLY

ISO/DIN 21368 "Adhesives – Guidelines for the fabrication of adhesively bonded structures and reporting procedures suitable for the risk evaluation of such structures" is a more generic version of DIN 6701 aimed at quality procedures in general industry, not only focusing on railway. ISO/DIN 21368 also follows a concept of group bonding and sealing applications in four categories. This allows the user to align the amount of quality measures with the complexity of the application.
A more generic standard is DIN 2304-1, "Quality requirements for adhesive bonding processes - Part 1: Adhesive bonding process chain".

9.2.3 FACADES

Quality control measures for structural glazing in façades are described in relevant standards such as EOTA ETAG 002, "Guideline for European Technical Approval for Structural Sealant Glazing Kits (SSGK) Part 1: supported and unsupported systems, EAD 090010-00-0404 "Bonded Glazing Kits and Bonding Sealants" and ASTM C1401 "Standard Guide for Structural Sealant Glazing".
EN 1279 part 6, "Glass in building - Insulating glass units - Part 6: Factory production control and periodic tests" provides a quality control scheme for primary and secondary sealants in an insulating glass unit.

9.3. DOCUMENTATION

9.3.1 ADHESIVE DOCUMENTATION

A standard document is the product data sheet. It is recommended to consider further documents provided by the supplier as they may contain valuable information for design, planning and manufacturing. Users must ensure that they use the latest version of the document.

9.3.2 WORKING INSTRUCTIONS

Working instructions should be part of the quality management system. They enable production staff to process sealants and adhesive in line with the aforementioned procedures. The instructions are made for each individual application and are based on specific information such as adhesion tests and they are the reference for audits that should take place regularly. As detailed, step by step process instructions, they describe how surfaces must be prepared, products applied and finished parts handled.

Work instructions should contain at least the following elements:

- Document name and number, allowing assignability to the respective assembly
- Revision number, date and validity time
- References to other relevant documents such as drawings, standards, guidelines, technical documentation, work or repair instructions, etc.
- Author responsible and date of creation, date of release
- List of products, parts to be joined, tools, test equipment, fixtures etc. to be used
- Conditions to be observed such as place of work, qualification of personnel, temperature range, relative humidity limits, acclimatization times, etc.
- Information on occupational safety and environmental protection
- Substrate preparation in detail
- Method of application including dimensions
- Waiting times
- Specifications for tests in the process. E.g. wetting tests and work samples
- Disposal instructions
- Measures in case of deviations from information given in the working instruction

The content of the work instructions is based on:

- Technical drawings. E.g. for the correct joint dimensions
- Test reports such as adhesion test results
- Product data sheet for relevant data and for general instruction on the use of the product
- Safety data sheets for environmental, health and safety instruction
- Other recommendations received from the adhesive supplier. For instance additional technical information beyond the product data sheet

Working instruction shall be:

- Correct from a technical perspective
- Complete and comprehensive, but concise
- Clear
- Checked and approved
- Close at hand
- Current and fully up to date

It has proven useful to include pictures and pictographs for individual steps because it improves readability under workshop conditions and avoids misinterpretation.

PHASE	PHASE DESCRIPTION
 208	Heavily soiled surfaces should first be cleaned off with a pure solvent, like Sika® Remover-208, to remove the worst of the soiling.
	Lightly abrade the contact area with a very fine sanding pad
	Remove the dust with a vacuum cleaner
 SA 100	Pre-treat the substrate with Sika® Aktivator-100 using a clean, lint-free rag or a paper towel. Change the rag frequently!
	Flash-off: 10 minutes (min) to 2 hours (max)
 SMM	Apply a thin continuous coat of Sika® MultiPrimer Marine, using a clean brush or a felt applicator
	Drying time: 30 minutes (min) to 24 hours (max)

Fig. 9.2 Example work instruction

Best practice is to involve the working staff in the creation and update of work instructions, which are also the basis of training for bonding work staff.

9.4. METHODS

As mentioned, one of the challenges with adhesive technologies is that there are only a few non-destructive quality control methods, so the focus is on error free application processes. The following methods support the quality manager in this respect.

9.4.1 TRACEABILITY

ISO/DIN 21368 requires traceability of products used in bonding processes. Adhesive applicators are required to document information such as product name for pretreatment and adhesives, batch numbers, expiration dates etc. Sika's data matrix code (DMC) is an available and easy option for the user to collect such information efficiently and accurately.

Fig. 9.3
Data Matrix Code (DMC) with hand reader

9.4.2 PRODUCT DETECTION

Various activators and primers contain luminescent ingredients which make treated surfaces glow temporarily when exposed to UV light. These solutions provide a visual detection method for verifying the application and are well suited to process control and safety requirements.

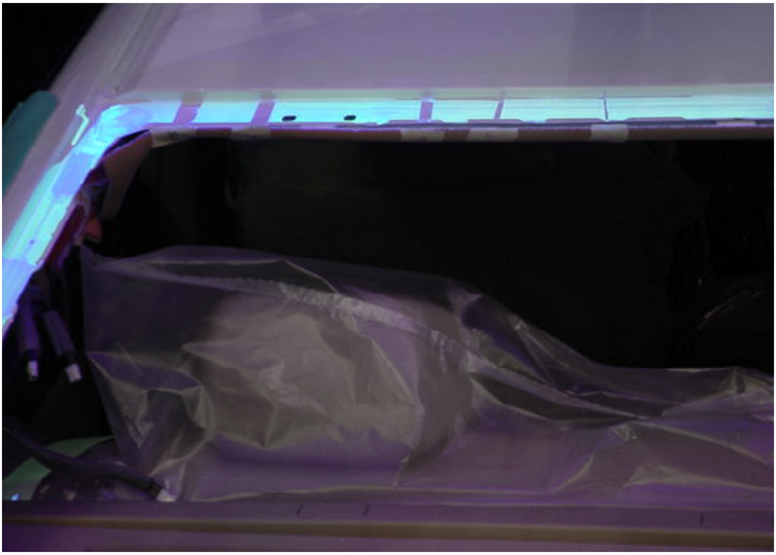


Fig. 9.4
Pinch weld under UV light with reflective pretreatment prior to adhesive application

9.4.3 ADHESION TESTS

Adhesion tests can be used for in-process control or other checks. Close attention should be paid to substrates supplied in batches. In case of doubt, adhesion testing in the quality control department is an efficient method to detect changes. Adhesion to the substrates can be determined by means of bead peel tests according to ISO 21194 / DIN 54 457. It is important that the tests are carried out on substrates that correspond exactly to the surface quality used in the production line.
The principle of the test is to stretch a cured adhesive bead by hand, assisted by using needle-nose pliers with a rotating motion, so that maximum peel stress is applied to the adhesive surface, as shown in the below illustration.

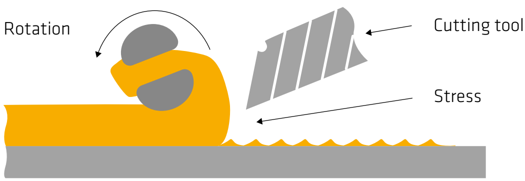


Fig. 9.5
Bead peel test schematic

At intervals of a few millimeters, the adhesive bead is repeatedly cut down to the substrate to concentrate the peeling force on one line and thus maximize it. Each cut is a new test of the adhesion between adhesive and surface. Sufficient tests to create a relevant statistic should be made. As an example, a 10 cm length with a cut each 5 mm would generate 20 single test results.

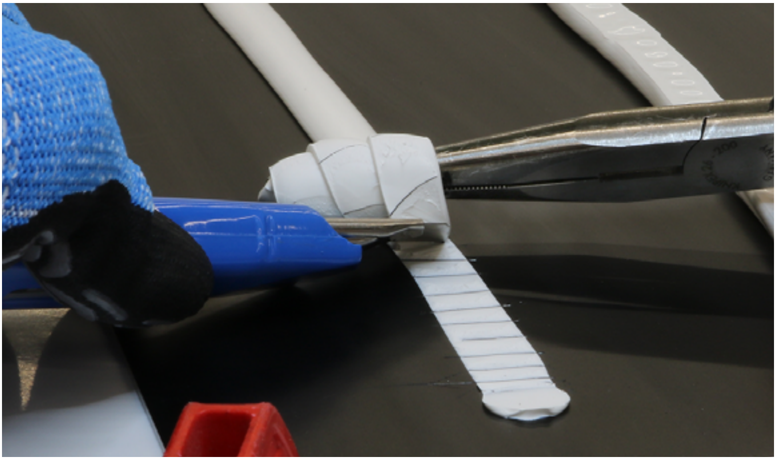


Fig. 9.6
Bead peel test under laboratory conditions

After 10 cm of peeling the test is complete and the fracture pattern is evaluated. The below photographs show examples of results according to DIN 54457.

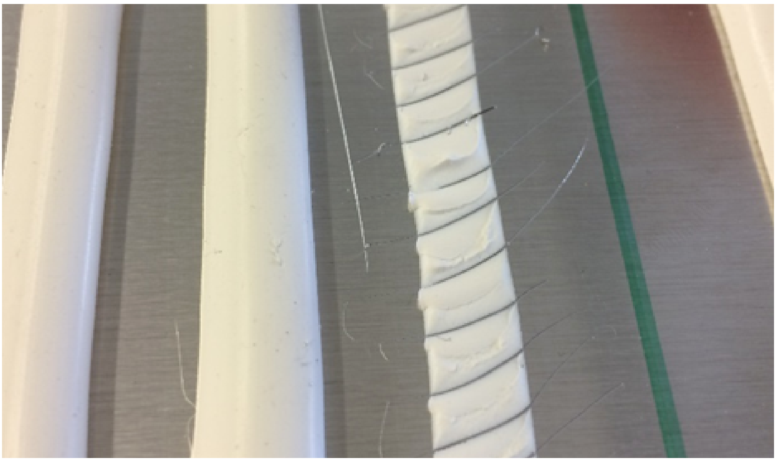


Fig. 9.7
Ideal adhesion with 100 % cohesive break

Fig. 9.8
Very poor adhesion with 100 % adhesion loss

9.5. CHANGE MANAGEMENT

The best plans and processes actively react to changes. Whether the substrates, the adhesives or the process changes, it is important to ensure the change does not have a negative impact. Such changes can be announced or unannounced and a good quality control system will be able to detect both of these, responding quickly and effectively. Control of incoming goods is an important task, as is having procedures to respond to information from suppliers of the various materials.
For bonding, precise definition of the surface quality is important, not only the specification of the base material.

Suppliers of substrates may not inform of changes if they are unaware that the surface of their product is important for adhesive bonding. This can happen if the material being produced is a commodity and used for a variety of applications.
This is especially critical with substrates such as coatings, plastics or molded parts. As an example, if the composition of paint is changed, the result may look normal to the paint shop, but the surface conditions for adhesive bonding may have changed negatively. Pretreatment systems for adhesives can largely compensate for fluctuations, but not beyond critical or previously unknown levels.
Communication between suppliers and users shall be organized in such a way that it is possible to react in both directions if necessary. The following tables are a typical solution between an adhesive supplier and user.

ADHESIVE SUPPLIER	USER	SUBSTRATE SUPPLIER
Change at adhesive supplier		
Information about changes with impact on user. For instance composition, performance, documentation, availability, process, production site etc.	Acknowledgment of information and implementation in the organization. Repeat tests as recommended by the adhesive supplier. Supply fresh substrates if required.	
Change at substrate suppliers		
Adhesion tests by laboratory if needed.	Inform adhesive supplier in case of substrate changes. Supply fresh substrates if required.	Information about changes with impact on substrate. For example composition, performance, documentation, availability, process, production site etc.
	Tests under production conditions. Update documentation if appropriate.	

Fig. 9.9
Supplier and user typical reaction to changes

The same can be applied for changes at the user that have an influence on the adhesive or the substrate. E.g. a new production process or method.
It is important to understand that any specific recommendation, like test reports or sales conditions, may render it invalid if one party decides not to follow the recommended procedures.

9.6. ROLES

The work to produce good quality products is a team effort. The table below describes common team roles and functions.

AREA OF RESPONSIBILITY	CHECKS AND CONTROLS	DEPARTMENT AND PERSON RESPONSIBLE
Ensuring consistent quality of substrates	Specification including name, brand, grade, supplier, chemical composition, etc.	Design and Engineering
	Contractual agreements specifying quality and condition of substrate. Duty to inform in the event of changes.	Procurement
	Checks on incoming deliveries including name, brand, grade, product characteristics, etc.	Quality Assurance (QA)
	Correct storage parameters such as temperature, humidity, prevention of soiling and first-in first-out stock rotation.	QA/Logistics
Preparation of substrates	Specification of mechanical surface preparation, chemical products, type of application and processing schedule.	Design and Engineering/ Adhesives technician/Adhesive supplier
	Correct storage temperature, humidity, prevention of soiling and use of stock by expiry date.	QA/Logistics
	Subjective checks for visible defects in primers, such as cloudiness, sedimentation, thickening, etc., plus checks on expiry date.	QA/Foreman
	Periodic checks on correct application procedures, for instance method of application, observance of recommended drying times, correct handling of primed components prior to assembly, etc.	QA/Adhesives technician/Foreman

AREA OF RE-SPONSIBILITY	CHECKS AND CONTROLS	DEPARTMENT AND PERSON RESPONSIBLE
Application of adhesive	Checks on incoming deliveries including name, brand, grade product characteristics, visual inspection of packs and periodic adhesion tests.	QA
	Correct storage temperature, humidity, conditioning of stock to room temperature and use of stock by expiration date.	QA/Logistics
	Subjective checks for visible defects in adhesives such as changes in consistency, flow behavior, etc., plus checks on expiry date.	QA/Foreman
	Periodic checks on correct application procedures for method of application, observance of specified open times, correct joint assembly sequence, waiting times prior to further processing, etc.	QA/Adhesives technician/Fore-man
	Keep records on products used and working conditions, for example batch numbers, temperature, humidity, technician name etc.	Adhesives tech-nician/QA

Fig. 9.10
Common roles and tasks

9.7. SKILLS AND EDUCATION

The successful use of adhesives is founded on the technical knowledge of designers, engineers and assembly personnel. It is important to continuously expand that expertise to keep pace with new developments, methods and techniques. Comprehensive training is available for adhesive bonding to support knowledge development and examples can be seen below.

Standards ISO/DIN 21368 or DIN 2304 request the installation of a “Supervisor in Charge”, who is a trained person responsible for bonding and sealing operations. This concept has proven to be effective and is recommended to enterprises that use adhesives in series production.

Along with standardization, several training courses including degrees have been established. The following are examples.
DVS® / EWF European Adhesive Bonder EAB.
DVS® / EWF European Adhesive Specialist EAS.
DVS® / EWF European Adhesive Engineer EAE.

Corresponding training is offered by a variety of organizations.
Fraunhofer-Institut IFAM, Wiener Straße 12, 28359 Bremen, Germany
TC-Kleben GmbH, Carlstraße 50, 52531 Übach-Palenberg, Germany
Industrieverband Klebstoffe e.V., Völklinger Straße 4, 40219 Düsseldorf, Germany
OFI Technologie& Innovation GmbH, Franz-Grill-Straße 5, 1030 Wien, Austria
Lijmacademie B.V., Ericssonstraat 2, 5121 ML Rijen, Netherlands
Istituto Italiano della Saldatura, Lungobisagno Istra 15a, 16141 Genova, Italy

9.8. CHECKLIST

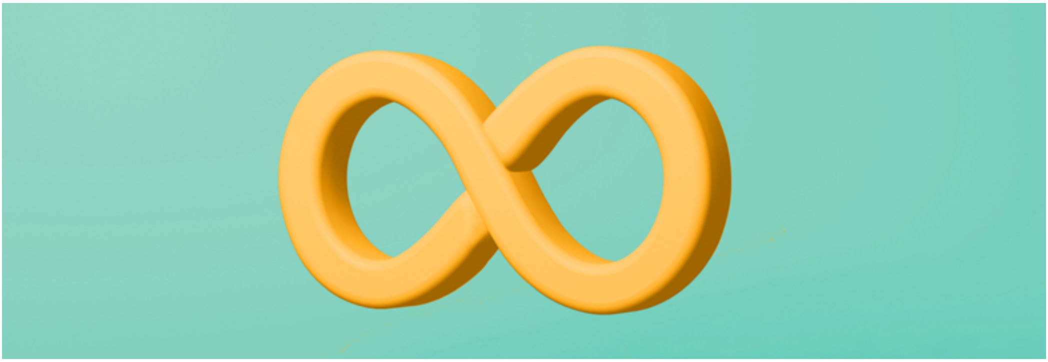
The following table shows important aspects for bonding and sealing applications. The list must be adapted to the specific requirements of each manufacturing environment.

ASPECT	DESCRIPTION
Joint design	Selection of materials Definition of surface quality Adhesives type, auxiliaries Dimensions such as thickness and width of adhesive joints Surface preparation Safety classification Certification
Tests	Adhesion and durability test Functional tests of bonded parts Application trials
Instruction	Description of the entire bonding and sealing process including dimensions, products and necessary conditions Training

ASPECT	DESCRIPTION
Environment	Designed area in the workshop Storage of products Temperature and humidity Surfaces have to be clean, dry and free of oil, grease, dust and loose particles.
Safety	According to the Safety Data Sheet
Checks	Correct product type, expiration date, etc Visual check of products and substrates for contamination or damages Climate conditions
Incoming goods	Quality checks of incoming materials such as substrates, adhesive and pretreatment products
Surface preparation	Application of surface preparation products Cleanliness of application aids. E.g. brushes or pads Protection of prepared surfaces from contamination Drying times
Application	Correct mixing Correct volumes Avoidance of cavities and voids Application devices working properly, for example correct mixing ratio
Joining	Defined joint dimensions, including spacers Fixation of parts
In-process checks	Testing of samples produced at the production line and then tested, often as lap-shear specimens
Curing	Waiting time Prevention of overload of the joint
Transport	Waiting time Prevention of overload of the joint

Fig. 9.11
Quality checks

10 LONG TERM SERVICE ABILITY



AN ADHESIVE BOND IS EXPECTED TO FUNCTION AS INTENDED THROUGHOUT THE LIFETIME OF THE BONDED PARTS. Elastic adhesive joints can meet this expectation for decades without maintenance or replacement, provided they are designed and manufactured correctly.

10.1. INFLUENCING FACTORS

Elastic adhesives and sealants are polymers and, as such, are organic substances which, in part, mean they undergo an aging process dependent on various influencing factors. The following table lists the aging factors that occur in most practical situations.

TYPE	SUB-GROUP	EXAMPLES
Chemical exposure	Water	Rain, condensation, rinsing after cleaning
	Operating supplies	Salt water, cleaning agents, alcohols, solutions, fuels, gases
Radiation	IR / Temperature	Sunlight Heat radiation. e.g. engines
	UV	Sunlight
Mechanical stress	Deformations	Thermal expansion of parts Torsional movements
	Loads	Part weight, wind loads, use cases such as loads, deformations, impacts etc.
Substrates	Permeability to radiation	Glass, plastics
	Sensitivity to stress cracking	Acrylic, polycarbonate, polystyrene, ABS, etc.
	Dimensional stability	FRP e.g. unsaturated polyester resin, wood and wood panel products
	Diffusion processes	Rubber profiles in contact with adhesives
Corrosion	Steel Aluminum Other oxidation	Missing corrosion protection of substrates, standing water

Fig. 10.1
Aging factors

The correct assessment of these factors is an essential prerequisite for the adhesive bonded or sealed components to reach their expected service life.

10.2. DESIGN

The type of construction has a significant influence on the aging behavior of sealants and adhesives. The following describes which considerations and measures are useful in this phase.

10.2.1 SUNLIGHT (UV RADIATION)

Ultraviolet radiation is a component of ordinary sunlight. This high energy radiation is the primary cause of damage to exposed surfaces of organic materials. UV resistance is the ability of the adhesive bond surface to withstand damage by sunlight, especially UV radiation.

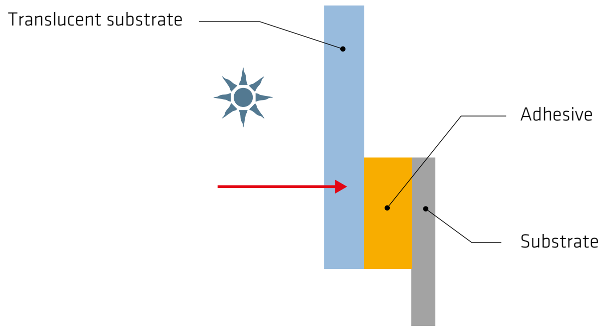


Fig. 10.2
UV on the adhesive bond face

Both transparent and translucent glass and plastics allow a certain amount of sunlight to penetrate the bonding surface. Silicon based adhesives can withstand this radiation without any significant impact on the bonding properties. With other elastic adhesives, the interface between the adhesive and the substrate must be shielded to protect the adhesive boundary layer. This layer is extremely sensitive, to the extent that, destruction of the outermost molecular layers is sufficient to significantly impair adhesion.
This can easily be prevented by covering the joint with an opaque material that is inherently UV-resistant, such as ceramic screen prints, protective strips or opaque paints. Adhesive joints shielded in this way are well protected from damage in the long term. Protective layers also hide the bond from view, which is usually desirable for aesthetic reasons. The following picture shows two possibilities of where the protection layer can be applied.

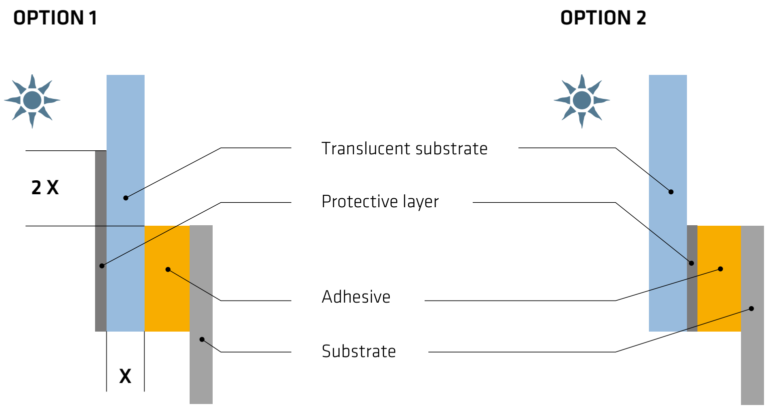


Fig. 10.3
Protection of the adhesive bonding face from sunlight (UV protection)

For option 1 the protective layer must overlap the adhesive joint sufficiently to protect the bond face from reflected light. It must be weathering resistant and opaque. The minimum overlap is at least twice the thickness of the translucent substrate.
For option 2 the protective layer must be UV stable, opaque, and compatible with the adhesive, which also includes the ability to transfer forces.

10.2.2 WEATHERING RESISTANCE

Weathering resistance is the ability of the exposed surface of an adhesive or sealant to resist outdoor exposure. Unsuitable products can show cracks, discoloration or staining before the expected end of design life. This is caused by the influence of sunlight, chemicals such as cleaning agents, temperature and mechanical stress.

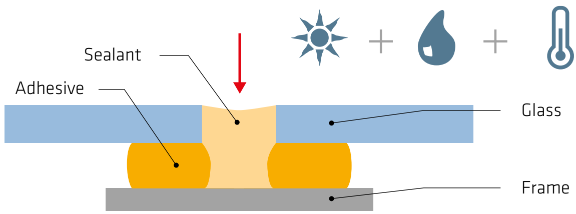


Fig. 10.4
Weathering resistance

To protect the load bearing adhesive joint from external influences, the joint can be filled with an additional layer of sealant. There are products available that achieve this with a single product only.

10.2.3 CORROSION

When bonding metals with adhesives, corrosion protection needs to be carefully considered. The purpose is to prevent the spread of corrosion under the adhesive layer, which eventually leads to failure of the joint, called bond line corrosion.
Although primers for adhesives contribute to corrosion protection, they are often not sufficient as a substitute to conventional corrosion protection such as a conversion layer. Passivation of metals creates conversion layers that are an excellent basis for subsequent treatments with organic coatings. Pretreatments for elastic adhesives and sealants are well suited for such surfaces, as they are compatible with methods such as anodization, hot dip-galvanization, phosphatation, etc.
Correct application of adhesives and sealants prevents the formation of voids, and thus the accumulation of water, which is the second most important measure to prevent bond line corrosion. The picture below shows what this means.

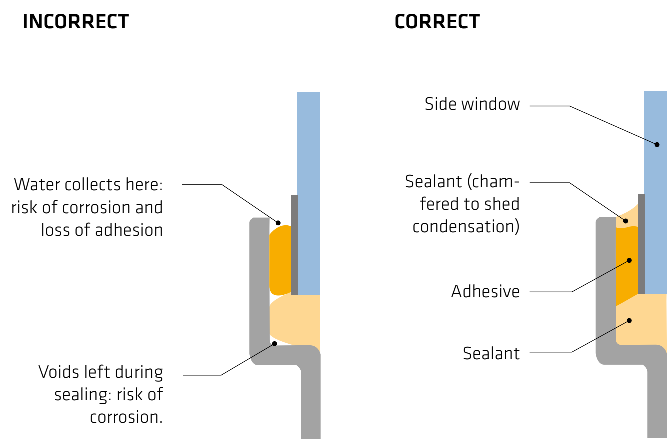


Fig. 10.5
Avoidance of corrosion and loss of adhesion with correct application of adhesive and sealant

10.2.4 CHEMICAL SUBSTANCES

While in service, adhesive joints can be attacked by different chemical products. In transportation vehicles, for example, it could be contact with cleaning agents, graffiti removers, water, anti-freeze, or fuels.
Factors of critical importance are the exposure duration and temperature, the type and concentration of chemicals, the joint design and the choice of adhesive or sealant.
The following example shows the influence of the joint design.

FILLED SEAM

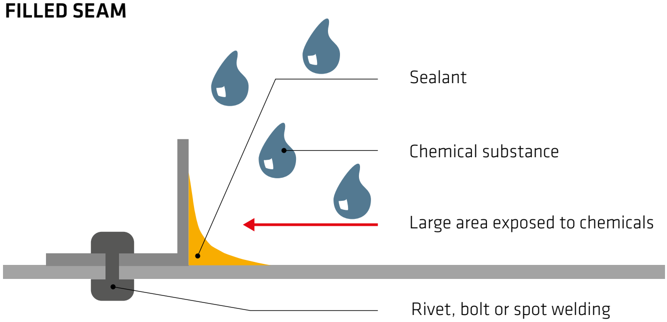


Fig. 10.6
External sealing results in high exposure to chemicals

OVERLAP

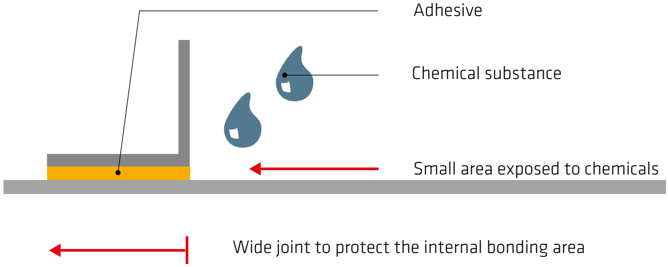


Fig. 10.7
Improved design

If adhesive or sealant joints are exposed to permanent or aggressive chemical attacks, it is essential to seek the advice of the adhesive manufacturer.

10.2.5 OVERHEATING

Because adhesives are polymers they need to be protected from excess heat. By way of comparison, their resistance is similar to that of many thermoplastics materials such as trim or paint. Attention must be paid to the use of sealants and adhesives in engine compartments, batteries, stoves and other very hot places. Silicone based products can withstand up to 200 °C and specially formulated heat resistant products temperature beyond 300 °C. As with other factors, the resistance to heat also depends on the duration of exposure.

In the event of massive overheating, for instance a fire, the adhesive may be destroyed and the joint may become compromised. If there is a risk that such destruction could cause personal injury or damage to property, additional fire resistant retaining measures must be built into the structure. These could be, for example, mechanical fixations.

10.2.6 MECHANICAL STRESS

Excessive mechanical stressing of bonded substrates causes irreversible damage to the adhesive layer. Stress levels shall therefore not exceed the maximum safe values determined through dynamic and static tests. Elastic adhesives exhibit a deformation behavior that is easily measured, so it is possible to construct prototypes and measure the degree of deformation under simulated service conditions. The stresses involved can then be determined with the aid of the appropriate dynamic moduli. This procedure enables design engineers to quantify the stresses accurately, so if necessary, they can modify the adhesive geometry or use a product with a different modulus.

10.3. SUBSTRATES

Substrates should be effectively managed during the planning phase to avoid the risk of premature degradation of the joint substrates, adhesives, or sealants. The following are some of the important substrate factors to manage.

10.3.1 METALS

Metals that are prone to corrosion shall be equipped with adequate corrosion protection, e.g. a conversion layer or a paint primer. Pretreatment products like activators or primers for adhesives are not designed to give comprehensive corrosion protection. In most cases primer layers protect the surface to a certain degree. Whether or not this protection is sufficient for specific processes is at the user's sole discretion.

10.3.2 WOOD AND WOOD PRODUCTS

Wood readily expands and contracts in response to changes in moisture content. Wood and wood products, including panel products and plywood, shrink when they lose moisture. To prevent the kind of movement caused by induced stresses referred to in the previous section, ensure selection of wood with balanced moisture content suitable for adhesive bonding.

10.3.3 FIBRE REINFORCED PLASTICS (FRP, SMC)

Sheets or components made from glass fiber reinforced polyester undergo a process of shrinkage during polymerization. I.e. curing, which continues for several weeks. Components made from this material should not be bonded too soon after manufacturing because the ongoing shrinkage process would place the component, and consequently the adhesive bond, under mechanical stress, possibly leading to premature bond failure. Alternatively, glass fiber components can be heat treated for a few hours to stabilize them, a process known as tempering or post-curing. Adhesive bonding of fiber reinforced polyester must therefore be restricted to tempered components or components that have been stored until shrinkage has finished.

An exception is sheet molding compound (SMC) components, comprising sheets of FRP pressed in a former, which are often bonded with adhesive directly after hot forming. The residual heat accelerates the curing speed of the adhesive. Adhesives used for this purpose are usually rigid 2-component types.

10.3.4 THERMOPLASTIC MATERIALS

When working with thermoplastic materials, the risk of failure in service due to environmental stress cracking (ESC) must be evaluated. ESC is the leading cause of plastic part failure, often visible by cracking or hazing of plastic parts. It is caused by a combination of different factors, such as the use of ESC sensitive materials, especially amorphous plastics like PMMA, ABS, PC, PS, etc., or contact with specific chemical agents during assembly or service life, or presence of stress concentrations, e.g., internal stress peaks from the thermoforming, or injection molding process, or from the use during the service life.

Fig. 10.8
Cracks in transparent thermoplastic material

Fig. 10.9
Cracks caused by an unsuitable adhesive

Plastic sheet and adhesive manufacturers issue guidance regarding the choice of adhesive products, joint dimensions, and surface preparation. Surface preparation might be needed to gain sufficient adhesion. Physical methods like plasma, corona or flame are common with thermoplastic materials. Chemical surface preparation on unstressed parts typically has a negligible impact on ESC. However, using an incompatible adhesive or joint design that results in high stress, e.g. by thermal expansion or insufficient elasticity, can lead to problems. Note carefully that some may contain high amounts of plasticizers that can cause ESC during service.

In addition, it is recommended to use stress free tempered components and install them without introducing local stress, e.g., cold bending. Adequate movement from thermal expansion must be allowed for by using adhesives in a sufficiently thick layer and control layer thickness in assembly. As noted in other sections, adequate UV protection must be used with translucent substrates.

Due to the complexity of ESC, it is recommended to run material compatibility testing e.g. acc. ISO 22088-1:2006 and complementary laboratory scale testing with the observation of prototype assembled components. While cracks are immediately visible on transparent substrates, be aware that they may take several months to appear on opaque materials.

10.3.5 TRANSPARENT SUBSTRATES

As mentioned, for transparent or translucent substrates, it is important to protect the adhesive bond line from sunlight, unless it is a silicone adhesive. The most common solutions have been noted in earlier sections.

10.4. EXAMPLE

The following example summarizes how the design phase can contribute to extended longevity of glass bonded to a frame:

- The glass has a ceramic frit to protect the adhesive from UV light. Not necessary if the adhesive is a silicone
- The frame has a suitable corrosion protection
- The visible joint was filled with a sealant that is resistance to weathering
- The adhesive is protected by an optional extra sealant layer
- All joints are smooth and flush to prevent accumulation of liquids

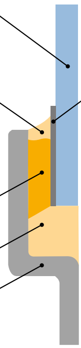


Fig. 10.10
Correct design of a simple bus side window

As noted, there are products available that can be used for both the adhesive bonding and the filling of the visible joint. This simplifies the process without sacrificing the simplicity of the above described solution.

10.5. PREDICTING DURABILITY

The durability of adhesives and sealants can be tested in various ways using artificial aging methods. This is mainly done in the laboratory, but can also be conducted outdoors. Within weeks to months, it is possible to assess whether an entire adhesive bond including substrates is durable or not. More fundamental tests, however, can take years.

10.5.1 LABORATORY

In order to test the durability of adhesives and sealants to substrates, test specimens are usually subjected to artificial aging, in which they are consecutively exposed to water, heat, cold, high humidity and temperature. The following table shows a typical sequence for construction elements. The details of this principle can be customized to simulate real conditions for each application segment. For an application inside a room, the cold exposure might not be necessary, assuming the room is not a cold storage facility.

	DURATION	AGING CONDITION	TEST CONDITION	TEST
1	7 days	23 °C / 50 % rel. humidity	23 °C	Peel
2	7 days	deionized water at 23 °C	23 °C	Peel
3	3 days	-30 °C	23 °C	Peel
4	3 days	80 °C	80 °C	Peel
5	2 hours	23 °C / 50 % rel. humidity	Conditioned 2 h at 23 °C	Peel
6	7 days	55 °C / 98 % rel. humidity	Conditioned 2 h at 23 °C	Peel

Fig. 10.11
Example of artificial exposure

To see how the different conditions affect adhesion, a peel test according to ISO 21194 is performed after each additional step. For this, a rotary movement is used to create a peeling stress. To achieve maximum concentration of the peeling forces, the bead is repeatedly cut close to the substrate. Afterwards, it is tested again to see if the adhesive can be peeled off. The result is ideal if it is not possible to separate the adhesive from the substrate, meaning full cohesive failure. To carry out a complete program of this type takes about 6 to 8 weeks.

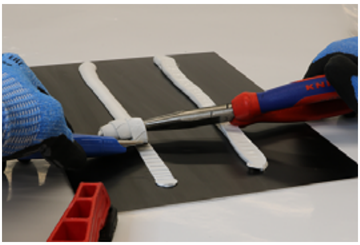



Fig. 10.12
Peel testing

To test the resistance to other factors such as sunlight, further methods are used during development and for the evaluation of new or complex designs. One method is the "QUV" tests, which exposes samples to UV light, temperature and humidity. The equipment can run different cycles, for example with UV light for a certain number of hours per day. This type of equipment is offered by various suppliers.

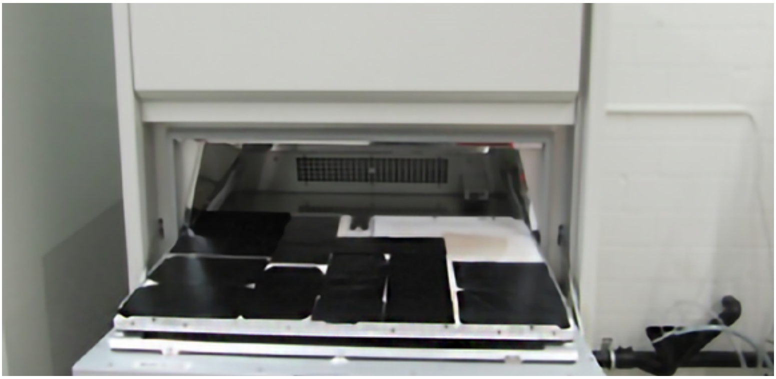


Fig. 10.13
Equipment to simulate sunlight, temperature and humidity

Such simulations do have their limitation. They can only simulate a part of what occurs to a sealant or adhesive in real life. But they are quick, efficient and allow comparison of products. A typical duration of exposure is between 1500 to 5000 hours.

Further methods include long term mechanical behavior under static and dynamic stress, but also exposing entire assemblies in salt spray chambers.

10.5.2 OUTDOOR WEATHERING

A subsequent durability testing step is to expose samples of adhesives and sealants to outdoor conditions in different locations from wet and cold to dry and hot. Specialist companies offer services to expose samples in locations such as Arizona and Florida that are known to be especially harsh climates for polymers. In addition, exposure in moderate climates, as found in Central Europe, should be included in such program. For adhesives and sealants it is common to expose specimens between 1 to 3 years, but can be longer.

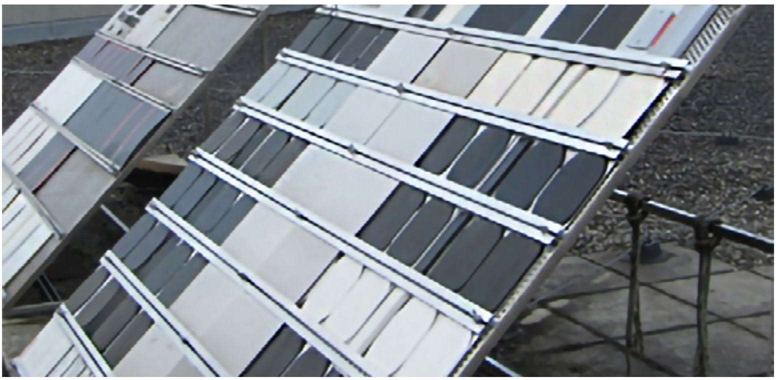


Fig. 10.14
Outdoor stand with adhesives and sealants specimens

10.6. MONITORING IN PRACTICE – EXAMPLE CASE

To ensure the results obtained from the durability testing methods described above are meaningful, it is crucial to compare with the results found in real life. Therefore a further durability testing step is regular inspection of vehicles that were bonded or sealed many years ago. By way of example, below is a case which describes what was found on a 20 year old train with an adhesive bonded driver cab.

10.6.1 DISASSEMBLY OF THE CAB

An inspection took place on an intercity tilting train (ICN train) of the Swiss Federal Railways SBB 20 years after its commissioning. The train was inspected from top to bottom to ensure safety. To check the 20 year old adhesive, SBB removed the driver's cab, which was bonded exclusively with elastic adhesives. This cab was made of fiberglass reinforced plastic, the car body of aluminum, both painted.
Firstly the adhesive joint was separated with an oscillating knife. Smaller joints can be cut with a utility knife or a special cutting wire, but here a power tool was more suitable and less laborious.

Fig. 10.15 Workers cut the sealant and adhesive with an oscillating knife

After cutting out the joint, the entire cab was lifted off the body. 20 years ago, it was lowered down in the same way before the adhesive was injected into the joint.

Fig. 10.16
The cabin is lifted from the body

Finally the adhesive was trimmed back to a thin layer. A white polyurethane product with SikaBooster®, i.e. curing accelerator, was used as the adhesive. The outer section of the joint was then filled with a black, weather resistant polyurethane sealant to create a flush finish on the outside.

Fig. 10.17
Remaining layer of Sika products after cutting

Once the cabin was removed, adhesion was tested and samples were taken. The samples were then analyzed visually, chemically and mechanically. The remaining layer adhered well to the substrate pretreated with black primer. If the results of the planned analysis are also good, the adhesive can now be applied directly to this layer.

10.6.2 RESULT OF ADHESIVE ANALYSIS

The analysis confirmed the adhesive bond was still in very good condition with no adhesion loss. The tensile strength showed an average drop of around 25 %, which is considered to be a good result considering the age of the vehicle. Safety factors built into the design and calculation phase ensured that the joint remained fully functional and secure. The recently introduced DIN EN 17460 (former DIN 6701) standard for the quality and safety of bonded joints in rail transport has also made a significant contribution to this.

Overall, the findings confirmed the high quality and durability of the products used. The result is even more impressive considering that a number of foreign substances were found in the adhesive, such as anions and copper. It is assumed those substances came from cleaning agents and from the pantograph of the electrically driven train.

The findings from such analysis are incorporated into the development of new products and they also provide a link to the artificial aging regimes mentioned before.

The good results are due to a combination of factors including the use of consistently high quality adhesives, joints and bonding processes designed in a way that supports a robust production method and ensures long lasting joints and adhesives applied and components assembled in the manner specified and planned beforehand.

As the quality of the adhesive was still good, it was not necessary to remove the old adhesive entirely. Once the cab is reassembled, the fresh adhesive can be applied directly onto the remaining layer of the originally applied adhesive.

10.6.3 REGULAR INSPECTION AND MAINTENANCE

Further inspections took place in the roof area, where sealants were used for different purposes. In some parts these no longer looked acceptable. Time, weather and probably also cleaning agents degraded their surface. They still fulfilled their function but were not in good condition and may have lost their function soon. For example water could enter and destroy the bond line below or wet the interior. Fortunately, it is relatively easy to replace the damaged material with fresh product. But it shows that periodic visual inspection of exposed joints is important to establish joint condition and identify any need for remedial work.

11 SAFETY AT WORK AND ENVIRONMENTAL SAFEGUARDS

ADHESIVES AND THE PRODUCTS USED TO PREPARE THE SURFACE FOR ADHESIVE BONDING ARE ALL CHEMICAL PRODUCTS and, as such, may contain substances that are potentially harmful to human health and to the environment.

11.1. EXPOSURE LIMITS

The occupational exposure limit is the threshold limit that defines the maximum concentration of an airborne substance to which a worker may be continuously exposed to e.g., for eight hours a day, five days a week, without experiencing any adverse impact on health. These threshold limits are based on a combination of toxicological studies and practical experiences and are subject to constant review as more scientific data become available. It is important to note that these limits and instructions for the safe use of chemicals are subject to national regulations. For users of chemical products, it is important to always follow the instructions given by the valid, local Safety Data Sheet (SDS).

The following application situations are known to pose an elevated level of risk:

- Chemical pretreatment products can contain volatile organic compounds (VOC's). When applying such products, extra attention must be paid to proper ventilation.
- Spray applications generate the risk of exposure to spray mist and splashes of products. When spraying, attention must be paid to appropriate ventilation and respiratory protection as well as eye and skin protection.
- Products applied at elevated temperature or heat cured, can lead to the risk of increased exposure to gases and vapours. When applying such products, attention must be paid to adequate ventilation and protection from burns.
- When cutting cured products, e.g., for repair, the generated heat may lead to formation of smoke and combustion gases. If this cannot be prevented it must be effectively extracted directly at the source by means of suitable ventilation.

The above information is indicative only and may not be sufficient. Always check the valid Safety Data Sheet before using any chemical product and carry out a risk assessment based on local conditions.

11.2. PERSONAL PROTECTION

The Safety Data Sheet of most elastic adhesives and sealants recommends the following protective measures:

PICTOGRAPH	DESCRIPTION
	Eye protection: Suitable goggles or safety glasses to protect from splashes or other contact with products.
	Hand protection: Chemical resistant gloves to prevent contact with products. Gloves need to be replaced frequently to prevent contamination of other objects like the application equipment.
	Skin and body protection: Long sleeves and appropriate trousers protect the skin from contact with chemicals. Contaminated cloths must be cleaned before use.

Fig. 11.1
Personal protective equipment

In case of inadequate ventilation wear respiratory protection. Respirator selection must be based on known or anticipated exposure levels, the hazards of the product and the safe working limits of the selected respirator.
The above information is indicative only and may not be sufficient. Always check the valid Safety Data Sheet before using a chemical product and carry out a risk assessment based on local conditions.

11.3. HYGIENE AND SAFETY

Fig. 11.2 Hygiene and safety measures

PICTOGRAPH	DESCRIPTION
	Wash hands: Wash hands after work and before eating, drinking or smoking.
	Eat and drink: Do not eat nor drink during use of chemicals. Keep food and drinks away from the working area.
	Fire: Do not smoke during the use of chemicals or next to chemicals. Especially pretreatment product can contain easily flammable solvents.
	Readiness: Do not use chemical products if you are unsure whether you know and apply the necessary safety measures. Always consult the Safety Data Sheet before use and seek advice from your EHS department.

The above information is indicative only and may not be sufficient. Always check the valid Safety Data Sheet before use a chemical product.

11.4. SAFETY TRAINING FOR POLYURETHANES

REACH is a regulation of the European Union, adopted to improve the protection of human health and the environment from the risks that can be posed by chemicals. REACH stands for Registration, Evaluation, Authorization and Restriction of Chemicals.
The potential of diisocyanates to induce asthma in people if exposure values are exceeded is well known. The European Union aims to reduce asthma cases by setting additional requirements for their continued use.
According to REACH regulations, the end users of polyurethane products with a diisocyanate concentration greater than 0.1 % have to be trained and certified on how to safely use such products. This also affects users of certain polyurethane based adhesives and sealants.
More information is provided at **https://safeusediisocyanates.eu**, where visitors are guided to self e-learning courses. Depending on the intended use of the polyurethane adhesives and sealants various training courses are available.

12 PROJECT CHECKLIST

TO KEEP A BONDING PROJECT ON TRACK AND ENSURE ALL TASKS ARE ACCOUNTED FOR it is advisable to use a project checklist. The checklist is a kind of roadmap to ensure the right things are dealt with in the right order.

PROJECT CHECKLIST

Assembled materials

- Material composition: name / brand / grade / supplier
- Surface condition: contaminations, release agents, plastics, etc.
- Thermal expansion: coefficient of thermal expansion
- Tendency to environmental stress cracking: ESC
- Tendency to corrosion
- Transparency

Function of adhesive joint

- Load transfer
- Bridge dimensional tolerances
- Accommodate thermal expansion
- Sound absorption
- Sealing
- Weatherproofing

Operating conditions

- Static loads
- Dynamic loads
- Tensile / Compression
- Shear / Torsion
- Chemical exposure: cleaning solutions, etc.
- Thermal exposure: sunlight, engines and other heat sources
- Radiation exposure: sunlight / UV

Application

- Production conditions: climate
- Production cycle times
- Production volumes
- Application equipment: applicator dispensers, pump units, etc.
- Green strength: handling strength requirements for further processing, dispatch, etc.
- Current solution in case of process update

General requirements

- Repair requirements
- Recycling

Fig. 12.1
Project checklist

13 OUTLOOK

MODERN ENGINEERS NOW CHOOSE AND USE ELASTIC ADHESIVES AS NATURALLY AS THEY USED TO USE MECHANICAL METHODS such as bolting, welding or riveting. It's no coincidence either because, over the past 40 years, elastic bonding and sealing has established itself as an essential technology in the designers and engineers portfolio, complementing or replacing mechanical fixing methods and enabling design and production of innovative and technically sophisticated products that are increasingly efficient to manufacture.

The evolution of elastic adhesives continues. New scientific knowledge helps create products that adhere to the most sophisticated modern materials with minimal effort. New crosslinking mechanisms and more innovative ways of using current adhesive and sealant technologies lead to further efficiencies and flexibility in product and process design. And of course, the choice of raw materials expands to ensure the latest findings in occupational safety can be accommodated without ever having to compromise on product performance.

We hope this book has helped you to overcome any inertia and get started with elastic adhesives, or has helped you to expand your existing knowledge. In either case, Sika technicians are ready to take you further on your journey to successful elastic adhesive bonding.

14 GLOSSARY

n	
1-component polyurethane adhesive	Adhesive containing isocyanate groups that cure on exposure to moisture. Other often used expressions are 1C or 1-part adhesive.
2-component adhesive	Adhesive formed by the addition of two components; main component and hardener. Other often used expressions are 2C or 2-part adhesive.

A-D	
Accelerators (SikaBooster®)	SikaBooster® is an accelerator which can be added to certain Sikaflex® products to make the curing process significantly faster and independent of air humidity. Example: SikaBooster® P-50
Accelerators (Sika® PowerCure)	Sika® PowerCure is application equipment technology specially developed to manually apply Sikaflex® products with SikaBooster®. Example: Sikaflex®-268 PowerCure
Activator	Solvent-containing adhesion promoters that increase the adhesion of an adhesive to a substrate. Unlike primers, activators do not have pigmentation or fillers, making them easier to apply than primers.
Adhesion	Adherence of an adhesive to substrate.
Adhesive break	Unwanted rupture or destruction of the adhesive in an adhesive or sealing joint. Most often the result of excessive loads, which lead to excessive strain.
Adhesive joint (bond line)	Gap between two components, which is filled with an adhesive.
Adhesive layer	The adhesive between two parts bonded together.
Aging	Evolution of the adhesive layer properties under the influence of time, mechanical load, temperature and other environmental conditions.
Assembly (bond-ing)	The process involves adhesively joining substrates. There are two mothods how this can be accomplished. See Wet and Dry Bonding.
Balanced moisture content	Moisture content of a material, especially wood, when allowed to stabilize relative to ambient levels of atmospheric temperature and air humidity.
Best before date	A date that marks the end of the shelf life. See also Shelf life.

A-D	
Bonding joint	See Adhesive joint.
Bond line	See Adhesive joint.
Breaking stress	Stress required to produce failure or fracture in a material.
Carbon dioxide	Carbon dioxide is a chemical compound with the chemical formula CO_2. Atmospheric CO_2 is the primary carbon source for life on Earth.
Clamping	Temporary securing of components in the desired position by mechanical means while the adhesive is setting.
Cleaner	Chemical agent used to clean surfaces prior to bonding.
Coefficient of thermal expansion	A factor that expresses the dimensional changes in a component as a function of temperature differences.
Cohesion	Inherent strength of a material.
Contact adhesive	Laminating adhesive, applied to both surfaces of the joint. Once ready, the adhesive surface is no longer tacky and the bonding force results only on contact of the two adhesives surfaces.
Crosslinking	Formation of chemical bonds between molecular chains. See curing.
Curing / Setting	Setting or hardening of an adhesive due to physical or chemical reaction. See crosslinking.
Curing conditions	Factors influencing the curing of adhesives, in particular temperature and, in the case of 1-component products, air humidity.
Dew point	Temperature at which a condensation of the air humidity occurs, depending on environmental temperature and air humidity.
Diisocyanate	An organic compound used for the reaction of polyurethane products such as adhesive, foams or coatings.
Diffusion	Migration of gases or liquids through materials. The curing process of 1-component polyurethanes, STP, MS and silicones is limited by the speed of diffusion of humidity, i.e. water molecules, through the hardened skin or layer of the adhesive.
Drying time	See Flash-off time
Dry bonding	Method of bonding whereby the adhesive is applied after the positioning of the components to bond. See in contrast Wet bonding.
Duromer	Cross-linked, mostly non-meltable plastics.

E-H	
Elasticity	The ability of an object to return to its original shape after being deformed by the application of force.
Elastomers	Polymers which can have high elasticity. They do not melt even at high temperatures. The elasticity is largely reversible. See also Elasticity.
Elongation at break	Elongation that takes place before a material fails or fractures. Usually measured in percentage of the initial stage.
ESC	Environmental Stress Cracking. Cracking of thermoplastics under internal or external mechanical stress, initiated or accelerated by chemicals, temperature or sunlight.
FEM	Finite element method. A mathematical method for the numerical solution of structural problems, i.e. calculations. FEM takes into account the mechanical properties of adhesives for the calculations.
Fillers	Additives, mostly inorganic, to improve the properties of the adhesive.
Final strength	Strength of an adhesive joint when the adhesive has reached full cure.
Flash-off time	Duration required for a primer, solvent, cleaner or activator to reach a state that will safely allow the process that follows it to be started, usually adhesive application.
Fracture energy	Energy that is required to cause a material to fail or fracture.
Galvanic corrosion	Corrosion due to the electrical contact of metals with different electrochemical potential such as aluminum or steel. The use of non-conductive adhesives can stop or minimize this effect.
FRP	Fiber reinforced plastics. Also GRP, glass reinforced plastic.
Handling strength	Strength level development at which the bonded assembly can be handled and passed on to the next stage of processing.
Heat resistance	The ability of a material to withstand heat without altering its state as a result of exposure to a specified temperature over a fixed period of time.

I-R	
Impact resistance	Resistance to abrupt forces. For instance when vehicles crash.
Joint width (adhesive)	The distance at which the adhesive bead overlaps the substrate in the direction of movement.
Joint width (sealant)	The width of the gap the sealant fills. Also named gap width.
Joint thickness	The distance between two substrates which is filled with adhesive.
Joint depths	The depths of a sealing. See also Joint width sealant.

I-R	
Migration	Plastics may show migration of ingredients like plasticizers or residual monomers or release agents on the surface, which can also influence adhesion or mechanical properties. These effects may only occur after aging.
Modulus of elasticity	Modulus of elasticity describes the ratio of stress to elongation on a rod under tension whose sides are unconstrained.
Movement by moisture	Expansion or contraction of components as a result of the humidity content variation in the material. Particularly applies to wood, but also affects other materials such as PA, brand name Nylon.
Non-sag properties	Resistance of an adhesive to collapse or slump when extruded as a bead.
Open or working time	Maximum period of time that may elapse between application of the adhesive and assembly of the joint.
Organic glass	Transparent plastics of the group thermoplasts such as PMMA and PC. E.g. Brand names; Plexiglas / Lexan. Thermoplasts are prone to environmental stress cracking. See ESC.
Pot-life	Period of time during which multi-component adhesives can be processed after their components have been mixed. Pot-life depends on the ambient temperature and the quantity of product mixed. It decreases with higher temperature and increased product quantities.
Pretreatment (Sika® Cleaner)	Mostly solvent based liquids to remove contaminations such as fingerprints, oils, grease or dust. Cleaners normally leave no residue on the surface. Examples: Sika® Cleaner P, Sika® Remover-208, Sika® Cleaner G+P
Pretreatment (Sika® Aktivator)	Solvent-based liquids containing adhesion promoters interact with the surface to change its surface energy. The solvents in activators also eliminate light contamination. For process control, some products include a luminescent dye detectable under UV light. Examples: Sika® Aktivator-100, Sika® Aktivator-205 LUM
Pretreatment (Sika® Primer)	Solvent-based coatings include adhesion promoters and fillers, which react with the surface to form a thin layer. Primers are typically black or transparent, and the layer is easily visible. For in-process control, some products contain luminescent dye that is detectable under UV light. Examples: Sika® Primer-207, Sika® Primer-507
Primer	A special paint coating designed to improve adhesion between the adhesive and the substrate. Primers can also have additional functions, such as reinforcing the substrate, reducing migration, and providing some corrosion protection.
Polyurethanes (Sikaflex®-200)	Adhesives and sealants based on polyurethane. With 1-component products, the water molecules from the air react with the isocyanate group of the prepolymer, finally forming a durable cross-link between prepolymer chains. Examples: Sikaflex®-221, Sikaflex®-268
Polyurethanes (Sikaflex®-600)	Adhesives and sealants based on Sika's Purform® polyurethane technology, engineered to minimize monomeric diisocyanate content to less than 0.1 %. Example: Sikaflex®-668

I-R	
Polyurethanes (SikaTack®)	Polyurethane based adhesives designed for applications such as windshield replacement in the automotive aftermarket. These products largely follow the principles that apply to the Sikaflex® range. Example: SikaTack® Drive
QA	Quality assurance.
Reactive adhesives	Adhesives that cure or set when exposed to heat, moisture, radiation, etc.

S-Z	
Sag resistance	See Non-sag properties.
Silan Terminated Polymers (Sikaflex®-500)	Adhesives and sealants based on silane terminated polymers (STP) that use a polymer binder containing reactive silane groups. Example: Sikaflex®-521 UV
Silan Terminated Polymers (Sikaflex®-900)	Adhesives and sealants based on polyurethane or silane terminated polymers with an additional B component to speed up the curing process. Example: Sikaflex®-953 L30
Sealant	Substance used to block the transfer of fluids or gases through joints.
Sealing joint	Gap between two components, which is filled width sealant.
Setting	Solidification of adhesive through physical or chemical process, or both.
Shear modulus	Defined as the ratio of the stress to the strain in a body that undergoes simple shear deformation.
Shelf life	Period of time that can elapse between the manufacturing of an adhesive and its latest use, provided the product is stored under controlled conditions. See also Best before date.
Silicones (Sikasil®)	1- and 2-component sealants and adhesives based on silicone technology for applications such as structural glazing on buildings, secondary seals of insulating glazing units, headlights, photovoltaic modules, home appliances and many more.
Skinning time	The time it takes to form a thin layer at the surface of an applied sealant or adhesive that differs in physical properties from the material beneath it.
Solids content	Non-volatile portion of chemical components such as adhesives or primers.
Solvent	Organic liquid that dissolves the base materials and other soluble adhesive components without changing their chemistry.
Spacers	Elastic parts, mostly self-adhering, used to control the dimensions of the adhesive layer. The shore hardness of the spacer should be equal to or lower than the one of the adhesive.
Setting-blocks	Rigid or partially elastic parts that absorb the inherent loads of assembled parts. Setting blocks can be used temporarily to bridge the time until the adhesive is sufficiently cured. Or they can be used permanently if the dead load exceeds the load capacity of the cured adhesive. The hardness of the setting blocks must be adapted to the intended use.

S-Z	
Strain	Refers to the movement when two materials joined with adhesive or sealants move under load. Strain is the percentual movement of the joint in relation to the initial stress free state.
Substrate	The base materials to be bonded to, e.g. glass, paint, plastics, steel, wood. Adhesives bond to the surface of the substrate.
Tack free	Time after which a sealant surface looses its tackiness so that dust no longer adheres.
Tensile lap-shear strength	Maximum stress that an adhesive bond joining two parallel surfaces can withstand in a single-lap joint when the joint is subjected to a shearing stress by applying a tensile load centrically to the two lapped substrates.
Tensile strength	Maximum stress that a material withstands under tension.
Thermoplastic	Plastics that soften under the application of heat, such as PVC, PMMA or ABS. Thermoplastic are know to be very sensitive to environmental stress cracking. See also ESC.
Thermosetting resins	Closely cross-linked macromolecules that do not undergo plastic deformation, even at high temperatures, for example polyester, and epoxy.
Thick-layer elastic bonding	Elastic bonding application where the thickness of the adhesive layer exceeds 3 millimeters.
Transmission (of light)	Ratio of the intensity of a beam of light passing through a body, related to its original intensity. Measured in the UV (organic glazing) and visible range (mineral glazing).
UV-radiation	High energy part of sunlight, mainly responsible for surface degradation of organic materials like paint, sealants, etc.
Viscosity	Resistance to flow exhibited by fluids or paste-like substances as a result of internal friction.
Wet bonding	Bonding process in which the adhesive is applied before the components are assembled, resulting in wetting of the surface of both substrates. See also dry bonding..
Wetting	Ability of liquids to disperse themselves uniformly over solid materials.

15 IMPRINT

15.1. DIVISIONS

15.1.1 COMPANY BEHIND THIS BOOK

Core Competencies | Sika Founded in Switzerland in 1910, Sika has developed into a successful global company with a leading position in the development and production of adhesive, sealing, acoustic, protective, and reinforcing systems and products.

15.1.2 SIKA INDUSTRY

Sika Industry, one out of eight target markets of Sika, delivers **innovative solutions** to the world's leading manufacturers and service providers in automotive OEM, commercial vehicles, automotive aftermarket, marine vessels, renewable energy, sandwich panels, industrial equipment, HVAC, home and commercial appliances, modular building, facades and fenestration and battery systems.

15.1.3 OUR CORE COMPETENCIES

A key factor in the success of Sika is its strategic focus on clearly defined core competencies. Our development and technical service teams draw from a broad **portfolio of technologies** in order to offer the most innovative solutions within each competency, namely: bonding, sealing, damping, reinforcing and protecting.

15.1.4 BONDING

Bonding joins materials with durability, strength, flexibility, and toughness. Our expertise in joining composites, glass, metals, and plastics opens possibilities to incorporate a broad range of materials into new designs. Sika bonding adhesive technologies increases the safety and endurance of end products, enable greater design freedom, and offer higher process efficiency.

15.1.5 DAMPING

Damping reduces vibrations of all wavelengths in fixed and moving objects resulting in lower reverberation and noise emissions. Sika baffle or pads products are designed for a wide range of both structure and airborne damping treatments. Noise inside vehicles – whether in a car, a truck, or a cruise ship – is silenced, thereby significantly increasing comfort.

15.1.6 PROTECTING

Protecting increases the durability of structures and preserves the materials of new and renovated objects. Sika solutions guarantee sustained protection for all types of materials against climatic conditions, chemical influence, pollution and fire.

15.1.7 SEALING

Sealing ensures insulation from the elements. Sika sealants are designed to withstand the most demanding environments with enduring flexibility. From facade elements to exterior joints on marine vessels, Sika sealants provide long-lasting barriers to wind, rain, sun and chemicals.

15.1.8 REINFORCING

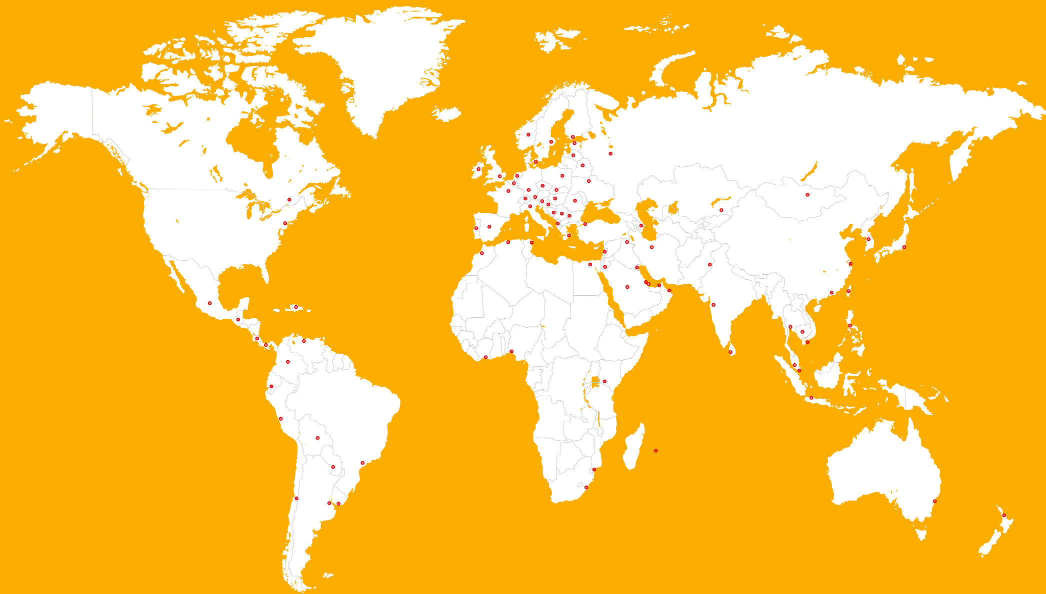
Reinforcing bolsters the carrying capacity of statically- or dynamically-stressed load-bearing structures in a targeted manner, from crash-resistant vehicle bodies to lightweight window frames. Sika reinforcing solutions place the strength where you need it, permitting optimal design and use of materials.

For further information visit our website at **industry.sika.com** or contact your local Sika company **(choose your country here)** .

15.1.9 LAYOUT AND GRAPHICS

Deck 4 GmbH, Zürich **www.deck4.ch**

GLOBAL BUT LOCAL PARTNERSHIP



WHO WE ARE

Sika AG, Switzerland, is a globally active specialty chemicals company. Sika supplies the building and construction industry as well as manufacturing industries (automotive, bus, truck, rail, solar and wind power plants, facades). Sika is a leader in processing materials used in sealing, bonding, damping, reinforcing and protecting loadbearing structures. Sika's product lines feature high quality concrete admixtures, specialty mortars, sealants and adhesives, damping and reinforcing materials, structural strengthening systems, industrial flooring as well as roofing and waterproofing systems.

DISCLAIMER

The information, and, in particular, the recommendations relating to the application and enduse of Sika products, are given in good faith based on Sika's current knowledge and experience of the products when properly stored, handled and applied under normal conditions in accordance with Sika's recommendations. In practice, the differences in materials, substrates and actual site conditions are such that no warranty in respect of merchantability or of fitness for a particular purpose, nor any liability arising out of any legal relationship whatsoever, can be inferred either from this information, or from any written recommendations, or from any other advice offered. The user of the product must test the product's suitability for the intended application and purpose. Sika reserves the right to change the properties of its products. The proprietary rights of third parties must be observed. All orders are accepted subject to our current terms of sale and delivery. Users must always refer to the most recent issue of the local Product Data Sheet for the product concerned, copies of which will be supplied on request.

SIKA SERVICES AG
Tueffenwies 16
CH-8048 Zurich
Switzerland

CONTACT
Phone: +41 58 436 40 40
industry.sika.com

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