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Elastic Bonding

The basic principles of adhesive technology and a guide to its cost-effective use in industry

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Elastic bonding is a tried and tested fastening technique that complements the existing range of traditional fastening methods. This innovative technology has recently begun to establish itself in various sectors of the manufacturing industry, most notably in the manufacture of domestic appliances and industrial plant. In essence it involves the bonding of two materials by an interfacial layer of permanently elastic adhesive that also performs a sealing function. One example is washing machine casings, which are routinely stiffened by bonding reinforcing profiles to the inside of the casing with elastic adhesives. Unlike welding, this leaves no marks or blemishes which would then have to be tooled out. Elevator doors are another example: Because there is no risk of thermal distortion when materials are bonded with adhesives, the doors can be constructed from thinner metal sections, with consequent savings in weight. However, the most important area of application for this innovative fastening technique remains the transport industry, where it is widely used in the assembly of road and rail vehicles.

The transport industry

People's willingness to use public transport depends to a very significant degree on the actual appearance of the buses and trams on their roads. When vehicles of older design are replaced by new ones of more attractive appearance, there is a marked rise in passenger numbers. Elastic bonding technology has contributed significantly to innovation in vehicle design, since it allows designers to create bold and unusual shapes by combining different materials such as glass, plastics and lightweight metals (Fig. 1).

The first use of adhesives to bond components and assemblies in the manufacture of buses dates back to the early 1980s. The modern bus industry now depends on elastic adhesives for a whole range of fastening applications – including roof assemblies, window glass, side walls, front and rear ends, floor pans and countless smaller assemblies (Fig. 2). But what attracts people to public transport is not just the external appearance of the vehicle fleet, but also the quality of the ride. An adhesive-bonded body assembly possesses greater torsional stiffness, dampens road noise and vibrations and generally helps to improve ride comfort.

Fig. 1:
Modern trams owe their stylish looks to a combination of glass, plastics and lightweight metals, bonded together with adhesives.

Economic benefits

In most cases, adhesive bonding is more economical than conventional fastening methods. It is also cleaner and uses less energy. Manufacturing

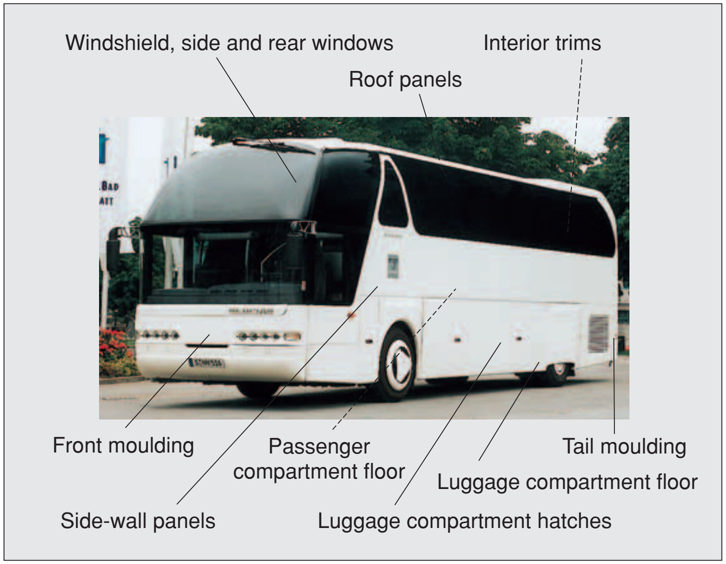

Fig. 2: Adhesive bonding applications on a modern bus

costs are directly proportionate to the number of components to be fastened together. Elastic bonding helps to reduce the number of individual components and encourages a modular approach to design and construction. Major assemblies such as complete roof elements can be pre-assembled, with their interior linings, and then bonded with elastic adhesives to the bodyshell. This method avoids the high stresses associated with welding. Thick-layer adhesive bonding is particularly effective in keeping down production costs. Larger manufacturing tolerances can easily be accommodated by simply increasing the thickness of the adhesive layer. Crucially, this can be done without affecting the mechanical strength of the joint to any significant degree.

Proven long-term durability

The durability of elastic adhesives, especially their long-term dynamic strength, can be demonstrated with reference to examples. The oldest buses with adhesive-bonded window glass have now been in service for over 15 years. During which time they have covered several million kilometres. And while their engines have had to be overhauled several times, the adhesive joints have continued to function perfectly throughout.

Elastic bonding also plays an important part in keeping down overall vehicle weight. The combined weight of a structural frame and a non-load-bearing sheet metal skin is replaced by adhesive-bonded body panels that contribute directly to the structural strength of the vehicle. This saves weight and increases torsional stiffness.

Weight savings

The boom in construction of rail and tram vehicles has led to the widespread use of elastic adhesive bonding as a joining technique. This trend has been reinforced by the concerted pressure on costs from rail operators, who want rail vehicles that are inexpensive to purchase and run. The latest generation of trams weighs up to a third less than their predecessors. With an average service life of 30 years in front of them, every kilogram of extra weight adds at least US $30 – $40 to running costs. Depending on the design of the vehicle, weight savings of this order can translate into cost savings of up to US $10,000 a year.

Less prone to corrosion

The fact that adhesive-bonded joints are less prone to corrosion also helps to keep operating costs down. As well as transferring any 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 (Fig. 3).

Correct joint design

As with any other fastening technology, adhesive bonding depends for its success on the observance of certain conditions. For example, the joint must be designed so that the bond face is sufficiently large to provide adequate strength. Correct joint design (see below, p. 20 ff.) can ensure that the joint is not subjected to peeling stresses or high static loads. The purpose of this handbook is to explain the principles and

Fig. 3:
Washing machine casings – a typical adhesive application

mechanisms of elastic bonding technology in clear language, and to serve as a reference guide for the cost-effective application of adhesive technology in industrial practice.

Elastic bonding compared with other fastening techniques

Adhesive bonding, whether of the elastic or hard-setting variety, differs fundamentally from traditional mechanical fastening methods (Table 1). In this chapter the salient characteristics of mechanical fastening methods and adhesive bonding technology are discussed and compared.

Table 1:
The principal industrial joining techniques – a comparison of features

Application criteria	Cost factors	Bolts/Screws	Rivets	Welding	Spot welding	Clinching	Clip fastenings	Structural bonding	Elastic bonding
Joining together dissimilar materials	Optimum choice/most economical use of materials	+	+	0	–	+	++	++	++
Calculability of joint, dependability of joint strength on temperature, creep under statistic load	Development costs, the need to take account of specific work processes and design requirements associated with the fastening technique	++	++	++	++	+	0	+/0	+
Thermal distortion	Additional processing stages	++	+	–	–	+	++	++	++
Occupational physiology (noise, chemical emissions)	Loss of man-hours as a result of illness	+	0	0	0	0	++	+/–	+/0
Sealing of joint	Additional work and expense in sealing joint	–	–	+	0	0	0	++/+	++
Susceptibility to corrosion	Preventive measures to guard against crack corrosion and galvanic corrosion	0	–	+	0	+	0	+	+
Waiting time between joint assembly and adequate strength attainment	Integration in the production cycle	++	++	++	++	++	++	+/0	+/0
Temperature-resistance of joint	Need to take account of extreme exposure conditions	++	++	++	++	++	+/0	+	+/0
Ease of disassembly	Ease of repair/effect on recycling costs	++	+	0	0	+	+	0	+
++ = very suitable, + = suitable, 0 = partly suitable, – unsuitable									

Lightweight construction

The need to join different materials together is particularly associated with lightweight construction, which deliberately exploits the specific performance characteristics of the various materials used. Synthetic materials and plastics, either fibre-reinforced or made up into composites, are also being used increasingly in lightweight construction. This means that fastening techniques have to accommodate a wide spectrum of different material properties. Elastic adhesives lend themselves particularly well to this type of application. Materials of low intrinsic strength can be fastened together flexibly and without localized stress peaks, resulting in a strong, load-bearing adhesive joint.

Computer-aided stress calculation

Computer calculations play a key role in the design and configuration of adhesive joints. Calculating the mechanical strengths of these joints, however, remains a complex and time-consuming task. Methods of calculation that are valid for rigid joints are only partly applicable to elastic connections between components. When it comes to building prototypes or setting up test arrays, engineers have to base their calculations on reference values which in most cases are only rough approximations (i.e. technical material data, such as tensile lap-shear strength, with appropriate safety margins factored into the calculations). Following extensive studies carried out at various universities and technical colleges, engineers now have access to a growing body of experimental design data that can be used to calculate the strength of an adhesive joint with the aid of finite-element methods (see chapter entitled *Calculating the strength of elastic adhesive joints*).

No thermal distortion

Some joining methods involve the application of heat to the components. This can cause thermal distortion and lead to deformation and breakdown of the material's internal structure. Correcting this kind of damage is usually very costly and labour-intensive. This type of manual work offers only limited opportunity for automation. Therefore in a series production environment, such corrective procedures are only carried out where absolutely necessary (e.g. filling and making good visual surface indentations caused by spot-welded thin-gauge sheet metal). None of this corrective work is necessary with adhesive bonding.

Physiological aspects

The impact on the health of the workforce is an important factor these days in evaluating the merits of a new technology. High noise levels and chemical emissions that are potentially harmful to health and the environment are undesirable contaminants. Adhesive bonding is a noise-free joining method. Some adhesives and the surface preparation products associated with them can release volatile and potentially harmful chemical substances. The actual health risks are, however, negligible provided the products are used as directed and proper safety precautions are observed (see chapter entitled *Safety at work and environmental safeguards*).

Bonding and sealing in one operation

Because elastic adhesives also act as sealants, they offer a relatively simple but effective way of protecting a joint against the ingress of gas or water. Adhesive-bonded joints can also be made resistant to chemical action more easily. Any special performance requirements of this kind need to be discussed at an early stage with the manufacturers of the adhesive products, so that both the adhesives and/or sealants and the design and configuration of the joint can be matched to the type of substrate and the chemical environment to which the joint will be exposed (in terms of chemical composition, concentration, temperature and exposure times).

The causes of corrosion are complex. As in the case of chemical resistance, adhesive bonding has been shown to offer better protection against crevice corrosion and galvanic corrosion than many other fastening techniques. Successful results depend on good workmanship and the use of adhesives that are themselves effective electrical insulators (i.e. with a specific resistivity in excess of 10^8 Ωcm).

Strength development …

Unlike mechanical joints, adhesive bonds do not immediately reach their maximum or ultimate strength. In many cases, however, assemblies can

… and waiting times

be handled and passed on to the next stage of processing before they attain their ultimate strength levels. On the plus side, the actual process of bonding the components together takes significantly less time than conventional joining methods. Process times have been further reduced by the development of new adhesives with short cure times and by adhesives based on a special two-stage cure system. The rapid initial cure provides sufficient early strength for the assembly to be handled and moved on through the production cycle, while the second, slower stage of cure provides the ultimate strength and the long-term temperature resistance required for the proposed application (Fig. 4).

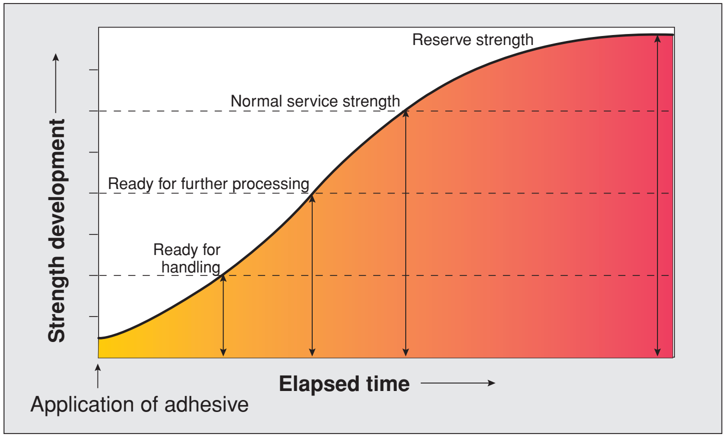

Fig. 4: Schematic diagram of strength development in an adhesive bond

Temperature-resistant to 100ºC

The temperature resistance of an adhesive-bonded joint is not as high as that of a conventional mechanically fastened joint. In many areas of application, however, the service temperature of the finished assembly is below 100ºC, which is below the critical temperature range for these adhesives. At the same time, the possibility of exceptional circumstances must be considered such as exposure to excessive heat in the event of fire. In such cases it may be necessary to provide additional mechanical fixtures as safety support systems, to prevent possible damage and injury from falling components or to prevent potentially hazardous leaks (e.g. from gas meters).

Separating the joint

It should also be possible to separate the joint at some later date without undue difficulty. This is important both for ease of repair and for recycling the individual components when they reach the end of their service life. These matters are discussed in more detail in the chapter *Disassembly and repairs*.

Mechanical properties

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 adhesive-bonded components to move relative to one another.

The principal mechanical properties of elastic-bonded joints may be quantified as follows. Their adhesive strength is in excess of 2 MPa. This is typically defined by determining the ultimate breaking stress in the tensile lap-shear test (DIN EN 1465). Elongation at break – i.e. the relative displacement of the bonded components before the joint fails – exceeds 200% of the applied thickness of adhesive, while the shear modulus is in the range 1 – 10 MPa (DIN 54 451). These values place the mechanical properties of elastic adhesives in between those of sealants and those of hard-setting adhesives. This accounts for the fact that elastic-bonded joints are capable of transferring forces and distributing stresses evenly.

Distribution of stresses

To ensure a durable connection and maximize the service life of the materials, an even distribution of stresses throughout the assembly is essential, particularly in the immediate vicinity of

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the joint. Conventional joining methods such as bonding with hard-setting adhesives, welding, riveting, screwing or bolting cause localized stress peaks at the joint itself.

Distribution of stresses …

The distribution of stresses can be clearly revealed in photoelastic models of joint assemblies made from a transparent material that becomes doubly refractive when subjected to stress. If a beam of polarized white light is shone through a stressed component, coloured lines appear when the object is viewed through a second polarization filter as a result of interference effects. These lines indicate areas of equal stress. If stress levels are increased, the sequence of coloured lines is repeated. Different lines of the same colour do not therefore necessarily indicate the same degree of stress.

The photographs below show specimen components made from clear acrylic or polycarbonate joined by different methods. In the side view of a bolted connection under load, the stress peaks around the bolt appear very clearly (Fig. 5a). The unstressed zones of the component appear yellow, e.g. in the upper right-hand corner. Moving from this unstressed area towards the bolt, a series of coloured lines are crossed until the zone of greatest stress is reached around the shaft of the bolt. A plan view of the connection reveals a similar picture: A high concentration of stresses around the bolt (Fig. 5b). At these points we can expect the component to suffer damage. A similar pattern of stress distribution is observed in components that are fastened together with rivets or spot welds.

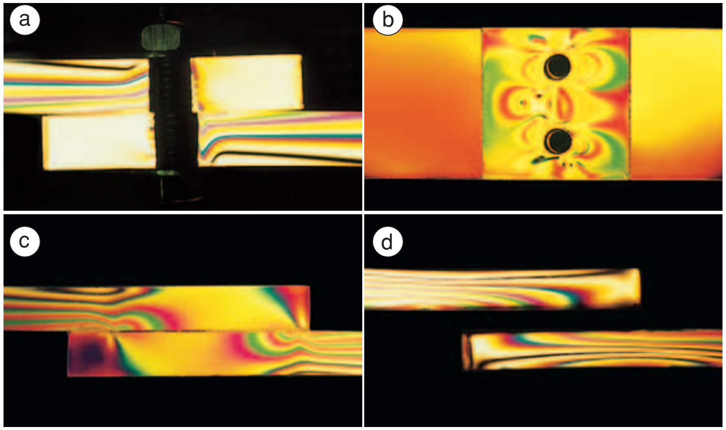

Fig. 5:
Stress patterns in photoelastic models:
- *a) Bolted connection under load (side elevation)*
- *b) Bolted connection under load (plan view)*
- *c) Thin-layer rigid adhesive bond*
- *d) Elastic adhesive bond*

… in mechanical fastenings and adhesive bonds

Figure 5c shows a thin-layer rigid adhesive bond, made with an acrylic adhesive cured under UV light. The expansion and deflection of the bonded substrates causes stress peaks at the ends of the overlaps, which is why the adhesive layer is beginning to break down at this point. The central portion of the bond face, on the other hand, contributes very little to the load-bearing capacity of the joint.

Figure 5d shows a thick-layer elastic adhesive bond, made with a black one-part polyurethane adhesive. Here, the stresses in the bonded substrates are uniformly distributed along the bondline, indicating that the whole of the bond face is contributing to the strength of the joint. Hence the fact that the breaking strength of elastic adhesive bonds increases in more or less direct proportion to the area of the bond face. By contrast, the stresses in rigid adhesive bonds are concentrated at the ends of the overlaps. This effect is even more pronounced in substrates with a low modulus of elasticity, as for example when the bond is made between plastic components rather than steel. In practice, this means that elastic-bonded joints can be designed to transmit relatively large forces simply by increasing the area of the bond face (length of overlap).

Tolerance compensation

Manufacturing tolerances measured in millimetres …

Manufacturing tolerances for components in the motor and general transport industries are usally measured in millimetres. This applies particularly to large components made from glass (e.g.

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… or even centimetres

curved windshields) or plastics (e.g. roof modules). Where structural support is provided by a welded steel or aluminium frame, the tolerances involved in the case of very large or very long components may well exceed a centimetre. Elastic bonding technology allows manufacturers to bridge gaps of this order without any loss of strength.

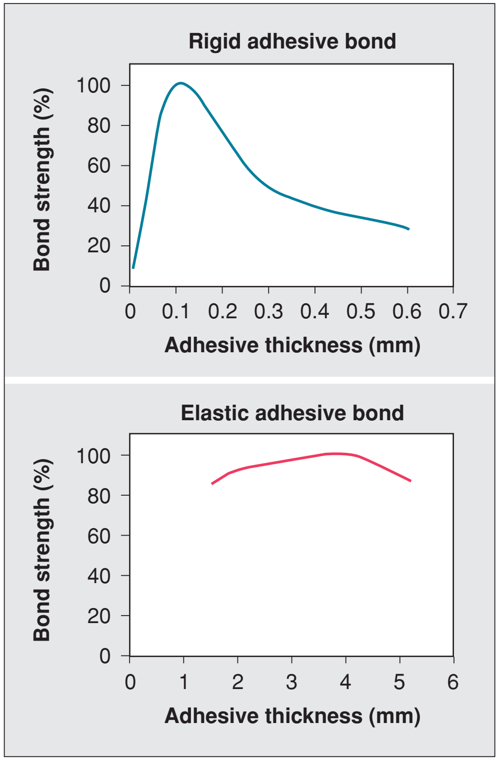


Fig. 6:
The effect of adhesive layer thickness on the strength of rigid and elastic adhesive bonds

Thickness of adhesive layer …

Where hard-setting adhesives are used, the strength of the joint depends very much on the thickness of the adhesive layer. Satisfactory results can be guaranteed only if the optimum thickness of adhesive is precisely maintained, and even slight deviations can reduce the strength of the joint by more than 50%. In the case of elastic adhesives, the actual thickness of the adhesive layer does not have a critical bearing on the strength of the joint, and variations can readily be accommodated (Fig. 6).

… and strength of joint

Peel strength

When force is applied in such a way that it tends to peel or prise apart the faces of an adhesive joint, the stresses involved very quickly reach critical levels. In such cases the applied load is no longer distributed over the whole of the bond face, but is concentrated along a narrow line at the edge of the joint (Fig. 7). The ultimate breaking stress of the materials is rapidly exceeded, resulting in tearing or total failure of the adhesive bond.

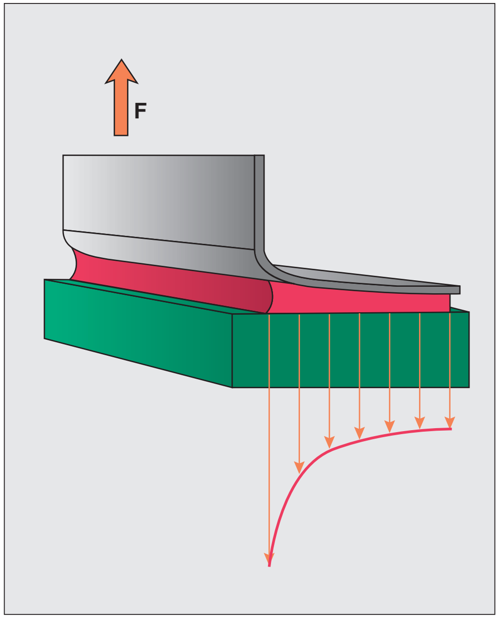


Fig. 7:
Stresses in an elastic-bonded adhesive joint subjected to a peeling force (F)

Thick-layer adhesive bonding

Thick-layer elastic-bonded joints “give” when subjected to peeling forces, allowing the load to be distributed over a wider area. Consequently the stresses within the bonded materials are kept at a relatively low level. The high tear propagation strength of polyurethanes – even where the adhesive layer has started to tear – prevents sudden and catastrophic failure of the joint. This forgiving behaviour means that damaged adhesive joints can be identified and repaired before total failure occurs. Nevertheless, exposure to peeling stresses must be considered at the design stage and avoided by appropriate measures.

Strength and safety

Fracture energy

The ability of elastic adhesives to undergo deformation and then recover makes them very forgiving when subjected to sudden stresses or brief periods of overload. In moving vehicles, such stresses may result from vibrations or from sudden impact with an obstacle. Whether or not an adhesive bond can withstand overloading without damage depends on its strength and above all on the fracture energy. This is the energy required to deform the adhesive layer before failure occurs. It is proportional to the area beneath the curve on a graph plotting the tensile lap-shear strain. The thin, rigid bond made with a high-strength epoxy adhesive exhibits very little deformation under high breaking loads. By comparison, the fracture energy required for the elastic polyurethane adhesive bond is much greater. The result is a significant gain in safety (Fig. 8).

To summarize, elastic adhesive bonding has proved its effectiveness in over 25 years of use under all types of service conditions. Correct joint design is critical: Because the strength of an adhesive is transferred only over the actual contact area, and the relation between contact area and transferred load for elastic adhesives is virtually linear, the bond face between the joined components must be sufficiently large to achieve the required strength.

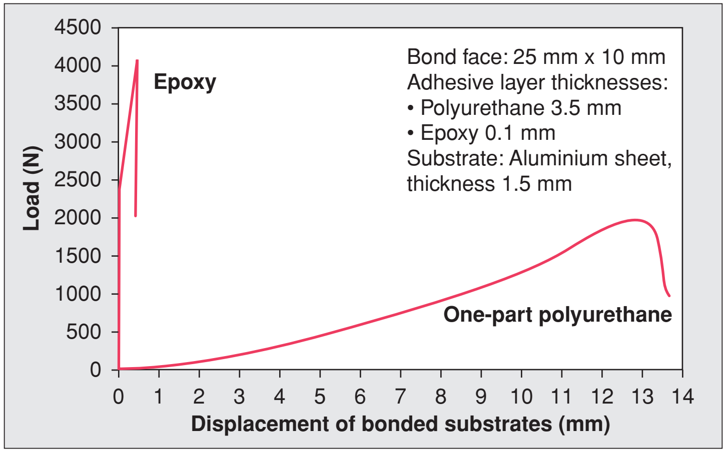


Fig. 8: Comparative tensile lap-shear test

Designing for adhesives

Since the strength of an elastic bond can be reliably predicted with the aid of the finite-element method (FEM) by factoring in the technical characteristics of the adhesive and the specific mechanical properties of the substrates, the required dimensions of the contact areas can be accurately calculated and the components forming the assembly can be developed accordingly. When designing joints for elastic adhesives, the basis for calculation is not the tensile lap-shear strength of the adhesive, but rather the modulus of shear and the residual strength values subsequent to vibration and ageing tests. Based on these values, the components can be specifically designed and dimensioned for elastic bonding.

Joint design for elastic bonding applications

Adequate dimensioning of joints

The successful and cost-effective application of adhesive bonding technology is critically dependent on correct joint design. The adhesive joint must be adequately dimensioned for the forces it will be required to transmit. Large static loads should be avoided wherever possible – especially where the joint is exposed to higher temperatures – and joints shoud be configured to support such loads and counteract peeling stresses. One example is illustrated in Figure 9.

Optimised connection form

The thickness of the adhesive layer must be sufficient to accommodate dimensional tolerances in components as well as any thermal movement. Attention must also be paid to the adverse effects that may result from climatic exposure. In all cases it is important to avoid standing water at the adhesive joint or seal. Figure 10 illustrates these principles in practice, using the example of a sandwich roof panel adhesive-bonded to a perimeter framing profile. If two parallel beads of adhesive are used to secure the

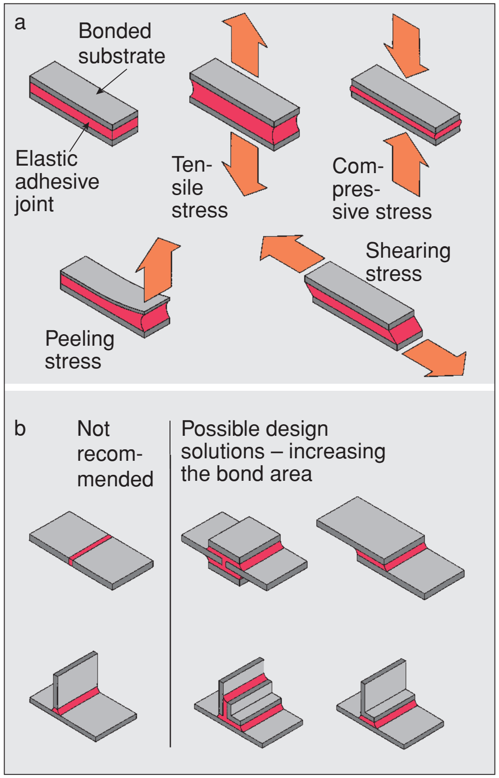


Fig. 9:
a) The basic types of mechanical stress
b) Alternative joint configurations for elastic-bonded joints

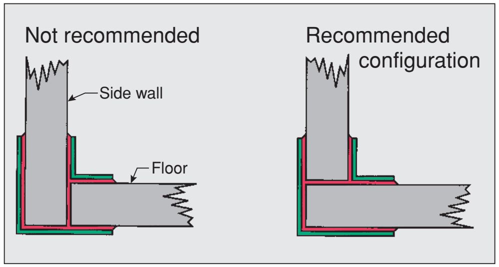


Fig. 9c:
The stresses induced by constant static loading in a truck cargo body can be minimized by careful joint design.

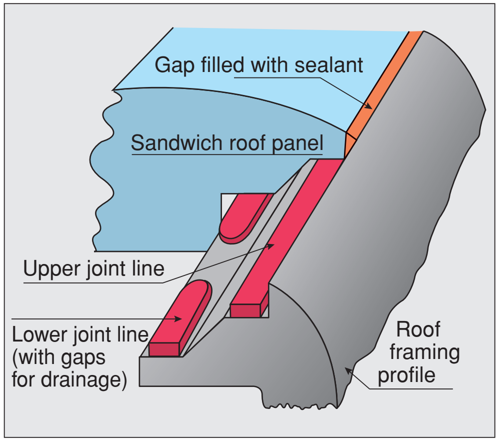


Fig. 10:
Detail of junction between adhesive-bonded sandwich roof panel and roof framing profile

roof panel, gaps must be left in the lower bead at regular intervals in order to drain and ventilate the cavity. Otherwise water collecting in the cavity as a result of condensation or water infiltration that goes undetected may lead to corrosion. Similarly, the sealed joint on the outside, at the junction between the roof panel and the framing profile, is located in the sloping portion of the roof to assist the rapid run-off of water.

Direct glazing

The earliest and best-known application of elastic bonding technology was direct glazing in car and bus production – meaning the installation of window glass by means of adhesives. This has now been standard practice in the automotive industry for more than 25 years. The main benefit initially was a reduction in glass breakages caused by excessively tight tolerances. A significant increase in torsional stiffness was later recognized as another plus. These and other secondary benefits such as automatable installation, improved weatherproofing, a quieter and more comfortable ride and greater aesthetic freedom for the vehicle designer, have resulted in the universal adoption of direct glazing technology throughout the automotive industry.

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 materials without compromising on safety, functionality or comfort. As a consequence, lightweight construction in the automotive industry has now attained a very high standard. In the meantime, direct glazing methods have been successfully adopted in other areas of manufacturing, notably in window construction (see chapter entitled *Elastic bonding in practice: A typical industrial application*). Here, the continuous adhesive bond between glazed unit and PVC frame serves to stiffen the whole sash assembly while also reducing its weight and increasing the visible glass area (Fig. 11).

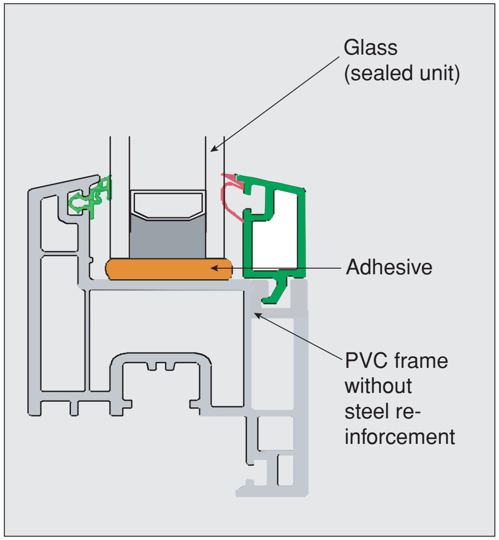


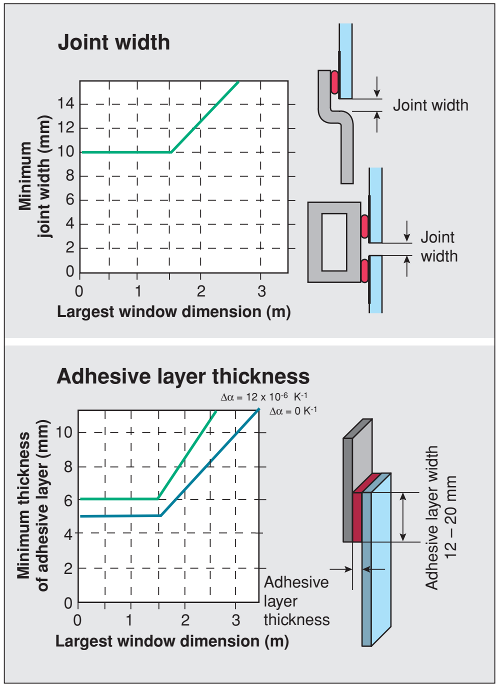
Fig. 11: Direct glazing in window construction

In exterior direct glazing applications, the interface between glass and adhesive must be shielded against UV radiation. The usual method is to apply an opaque ceramic screen-printed border to the glass, with a transmittance value of not more than 0.1%, or a correctly dimensioned cover strip for light of wavelengths between 400 and 500 nm. Guidelines for the dimensioning of adhesive joints in direct glazing applications are given in Figure 12.

Sheet metal vehicle bodies

The sheet metal skins of vehicle bodies used to be spot-welded onto a structural frame. The welds created 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 labour-intensive process unnecessary. Anti-corrosion paint coatings remain intact, which prolongs the life of the assembly. The natural damping properties of the elastic adhesive

Fig. 12: Dimensioning adhesive joints for direct glazing



extend the vehicle's operating capabilities. Last but not least, adhesive bonding opens up the possibility of using lightweight materials such as aluminium, glass-fibre-reinforced plastics (GRP) or sandwich panels.

Calculating the strength of elastic adhesive joints

In technical data sheets, the strength of an adhesive is generally stated in terms of its *tensile lap-shear strength*, which is 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 (Fig. 13).

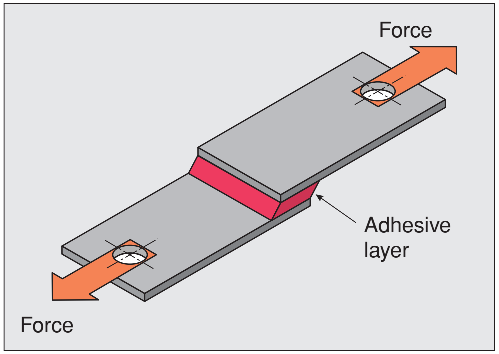


Fig. 13: Single lap adhesive joint used in tensile lap-shear test

Additional safety factor

Tensile lap-shear strengths are determined under ideal laboratory conditions using small test pieces. When calculating the design strength of larger assemblies, engineers have to multiply these laboratory figures by an appropriate reduction factor. Even where all the adverse influences on an adhesive joint are known, it is advisable to factor in an additional margin of safety to allow for any fluctuations in quality during the manufacturing process, so that the results of the strength calculations will always err on the safe side. Generally speaking, more satisfactory results are obtained by carrying out tests on the actual component or assembly. And in many cases it is necessary to test the adhesive joint by applying compressive or tensile loads before the final design calculations can be performed.

Since the effect of stress peaks at the ends of the overlaps can be discounted in bonds formed with elastic adhesives, it is not normally necessary to calculate the optimum ratio of substrate thickness to length of overlap.

Reduction factors

One-part polyurethane adhesives belong to the group of substances known as elastomers, and as such their mechanical material properties are highly dependent on service temperature and the duration of any exposure to stress. The changes in the strength and stiffness of the elastomer when the temperature and/or the period of exposure to stress are increased can be roughly quantified by applying the reduction factors plotted on the graphs below.

f_T: Temperature

The reduction factor for the effects of temperature exposure on a structural adhesive was determined with the aid of a tensile lap-shear test (Fig. 14). The strength of the adhesive decreases with a rise in temperature.

f_t: Constant static loading

The results of creep rupture tests on single-lap joints yielded the reduction factor for an adhesive bond subjected to constant static loading (Fig. 15). The strength of the adhesive decreases with increased exposure. In constant-load tests of this kind, particularly at higher temperatures, creep strain is observed in the adhesive layer.

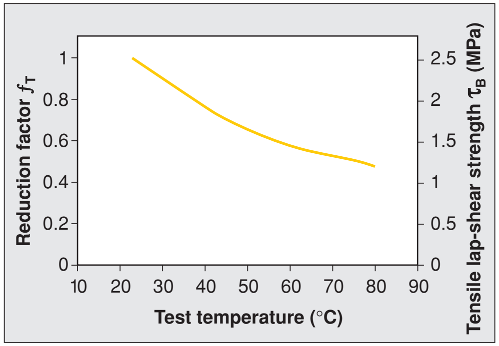


Fig. 14: Reduction factor: The effect of temperature

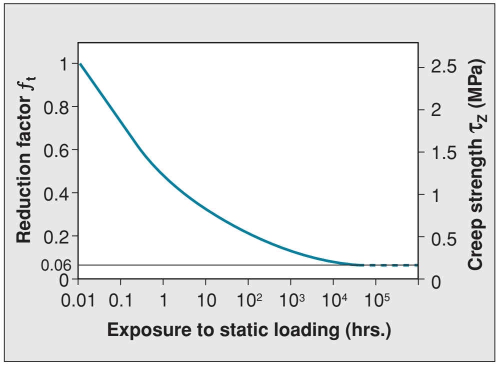


Fig. 15: Reduction factor: The effect of constant static loading

For this reason, a safety factor of at least 2 should always be included in the design calculations.

f_Z: Dynamic stress

The fatigue behaviour of adhesive bonds is tested by subjecting a test piece to dynamic load cycling. When the test values are plotted on a Wöhler chart, the appropriate reduction factor for prolonged exposure to dynamic stress can be read off (Fig. 16). As the number of cycles is

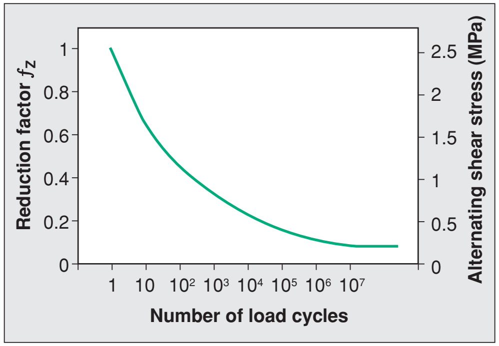


Fig. 16: Reduction factor: The effect of prolonged exposure to dynamic stress

increased, the amount of alternating shear stress that the adhesive layer can withstand is progressively decreased until the adhesive attains its service life resistance at around 20 million cycles, i.e. no further reduction in strength is observed after this point.

Multiaxial stress

Normal stress theory

Where a number of stress components are at work in different planes, their values can be mathematically adjusted to produce a compound or equivalent stress. To determine the equivalent stress 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.

$$\sigma_V = 0.5\sigma_Z + 0.5\sqrt{\sigma_Z^2 + 4\tau^2} \qquad (1)$$

where

σ_V	Equivalent stress
σ_Z	Tensile stress in the adhesive layer (tensile force: area of bond face)
τ	Shear stress in the adhesive layer (shear force: Area of bond face)

Sample calculations

Constant static shear stress

To estimate the required area of the bond face in joints subject to a constant static shear stress, the minimum safety factor of 2 combined with a reduction factor of 0.06 for exposure to constant static stress gives a design figure of 3% of the tensile lap-shear strength of the adhesive:

$$A_K = S_K \frac{F_{Shear}}{\tau_B \cdot f_t} \Rightarrow A_K = 2\,\frac{F_{Shear}}{\tau_B \cdot 0.06} \qquad (2)$$

where

A_K	Area of bond face
S_K	Safety factor
F_{Shear}	Shearing force
τ_B	Tensile lap-shear strength
f_t	Reduction factor for exposure to constant static stress

Standard design figure: 3%

As a general rule, the above value of 3% of the tensile lap-shear strength may be used as a standard design figure in calculations involving constant static stress.

Stresses acting on a bus windshield in an accident

Figure 17 illustrates in schematic form the forces acting on the windshield of a bus in an oblique frontal collision. The following sample calculation shows how the safety factor is estimated.

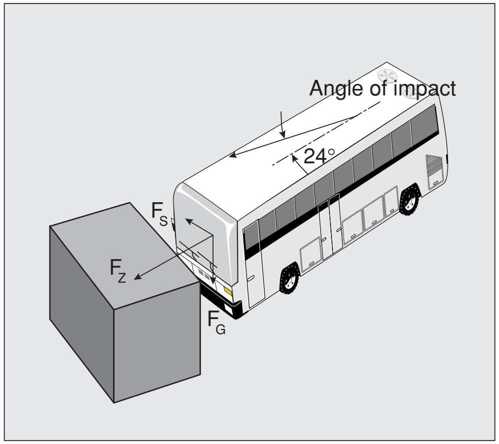


Fig. 17: Stresses acting on the adhesive bond of a bus windshield in an oblique frontal collision with a stationary obstacle

The windshield's own mass of 80 kg imposes a constant shear stress on the adhesive bond. To determine the gravitational force involved, the mass of the windshield is multiplied by the gravitational acceleration:

$$F_G = 80\ \text{kg} \cdot 9.81\ \text{m/s}^2 = 785\ \text{N} \tag{3}$$

where
F_G Gravitational force

In the supposed collision, the vehicle decelerates from 80 kph to 0 kph in 0.2 seconds. During that time it covers a distance of approximately 2 m. The windshield is briefly subjected to a maximum acceleration of approximately 120 m/s² (12 g approx.). Since the vehicle in this example hits the obstacle at an angle of 24º, the forces acting on the windshield consist of a tensile and a shear component:

Tensile and shear forces

$$F_Z = 80\ \text{kg} \cdot 120\ \text{m/s}^2 \cdot \cos 24° = 8800\ \text{N} \tag{4}$$

$$F_S = 80\ \text{kg} \cdot 120\ \text{m/s}^2 \cdot \sin 24° = 4000\ \text{N} \tag{5}$$

where
F_Z Tensile force acting on the windshield
F_S Shear force acting on the windshield

The area of the bond face for the windshield is calculated by multiplying the overall length of the perimeter joint (7 m) by its width (15 mm):

$$A_K = 7000\ \text{mm} \cdot 15\ \text{mm} = 105{,}000\ \text{mm}^2 \tag{6}$$

where
A_K Area of bond face

The standard windshield adhesive used has a tensile lap-shear strength of 4 MPa. Exposure to sunlight will inevitably cause the adhesive layer to heat up, so in this example a reduction factor of 0.5, corresponding to a temperature of 60ºC (see Fig. 14), has been applied. To estimate the safety factor for this adhesive joint, the tensile lap-shear strength multiplied by this reduction factor is divided by the equivalent stress (equation 1):

$$S_K = \frac{\tau_B \cdot f_T}{\sigma_V} = \frac{\tau_B \cdot f_T}{0.5\sigma_Z + 0.5\sqrt{\sigma_Z^2 + 4\tau^2}} \tag{7}$$

where
S_K Safety factor
τ_B Tensile lap-shear strength
f_T Reduction factor for temperature exposure
σ_V Equivalent stress

Prestressing

The (pre)stressing of the adhesive layer due to static loading must also be taken into account when considering the compound stresses resulting from the collision. The various forces involved (equations 3 – 5) operate for different lengths of time and at right angles to each other. To estimate the safety factor, therefore, their values in equation 7 are multiplied by different reduction factors (1 for short-term loading, 0.06 for constant static loading). The common plane on which these forces act, and from which the resulting stresses can be calculated, is the bond face A_K.

$$S_K = \frac{4\,\frac{\text{N}}{\text{mm}^2} \cdot 0.5 \cdot 105{,}000\ \text{mm}^2}{0.5 \cdot \frac{8800\ \text{N}}{1} + 0.5 \cdot \sqrt{\left(\frac{8800\ \text{N}}{1}\right)^2 + 4\left[\left(\frac{785\ \text{N}}{0.06}\right)^2 + \left(\frac{4000\ \text{N}}{1}\right)^2\right]}} \tag{8}$$

$$S_K = 11$$

The estimated safety factor for the compound stresses at work here shows that this particular adhesive joint possesses adequate reserves of strength.

Stress resulting from temperature changes

Thermal expansion

To a greater or lesser degree, temperature changes produce linear expansion or contraction in all materials. Where materials with different coefficients of linear expansion are joined together with an elastic adhesive, the adhesive must be capable of undergoing deformation, and the adhesive layer must be of sufficient thickness to accommodate that movement. Taking a bus roof as an example, the calculations below illustrate the method for determining the required thick-

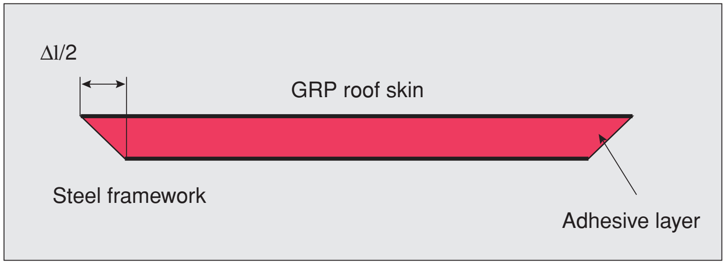


Fig. 18: Stresses in an adhesive bond resulting from differential thermal expansion

ness of adhesive (Fig. 18). A GRP roof panel 8 m in length is to be adhesive-bonded to a structural steel framework. The maximum temperature difference is assumed to be 70 kelvin (K), based on a projected rise in temperature from 20ºC to 90ºC in summer.

$$\Delta l = l_0 \cdot \Delta\alpha \cdot \Delta T \qquad (9)$$

$$\Delta l = 8\ \text{m} \cdot 8 \cdot 10^{-6}\ \text{K}^{-1} \cdot 70\ \text{K}$$

$$\Delta l = 4.5\ \text{mm}$$

where

Δl	Difference in linear expansion
l_0	Length of object
$\Delta\alpha$	$= \alpha_{GRP} - \alpha_{Steel}$ The difference in the coefficients of linear expansion (reference values: $\alpha_{GRP} = 20 \cdot 10^{-6}\ \text{K}^{-1}$, $\alpha_{Steel} = 12 \cdot 10^{-6}\ \text{K}^{-1}$)
ΔT	Temperature difference

Minimum thickness of adhesive

In the case of a roof assembly that is free to move at both ends, the change in length at either end is half of the total differential movement, i.e. 2.25 mm. As a general rule, the thickness of the adhesive layer must be greater than the total change in length. This ensures that the maximum shear stress undergone by the adhesive layer at either end does not exceed 50%. In this example, therefore, the minimum thickness of the adhesive should be 4.5 mm. Additional design criteria for the maximum permitted movement of the adhesive layer are given in Table 2.

Table 2: Maximum permissible movement of adhesive layer

	Thermal movement (discounting restraining force of adhesive)	Accident (e.g. derailment	Loading and unloading	Normal service operation (dynamic stresses)
Tension/Compression (relative to width of adhesive/sealant layer)	**20%**	**20%**	**20%**	**10%**
Shear (relative to thickness of adhesive/sealant layer)	**50%**	**50%**	**50%**	**25%**

The finite-element method in adhesive joint design

Solving problems by mathematical approximation

The finite-element method (FEM) is a powerful mathematical tool for the numerical solution of a whole range of strength problems associated with elastic and plastic materials. It is based on the calculation of linear equation systems with the aid of a computer. The system that is to be calculated, known as a structure, is subdivided into a network or grid of smaller elements that are linked together via nodes. By dividing up the structure into a finite number of elements, an approximate solution to the problem can be arrived at. The larger the number of elements – or the finer the network – the greater the accuracy of the solution. In FEM simulations, joints made with elastic adhesives are typically modelled using shell, spring and volume elements. The last two options are explained in more detail below.

Modelling with spring elements

Three stiffnesses

In a whole vehicle simulation, it is helpful to use spring elements for modelling because the adhesive joint can then be represented by means of relatively large elements. The basic rule of thumb is: The higher the number of elements, the better – i.e. finer – is the resolution of the adhesive joint. In modelling with spring elements, only the three stiffnesses for translational movement are factored into the equation: Two springs for the stiffness in shear and one spring for tension/compression. These three spring elements are decoupled from each other. A rotational stiffness is represented by several adjoining spring elements.

Adhesive joint as spring element

For purposes of modelling the adhesive layer by means of spring elements, the mechanical characteristics of the adhesive joint are stated as the generalized elasticity factor or stiffness. This is expressed in the same physical units as the modulus of elasticity. The spring constant for an adhesive-bonded joint can then be calculated by multiplying the stiffness value – a dimensionless quantity – by the known dimensions of the joint (Table 3). This allows the adhesive joint to be represented as a spring element in the overall structure being calculated.

$$k = c \cdot \frac{A_K}{d} \left(\frac{N}{mm}\right) \qquad (10)$$

where

k Spring constant for adhesive joint
c Stiffness
A_K Area of bond face
d Thickness of adhesive layer

This spring element is also used to check the adhesive joint geometry, bearing in mind that the maximum permissible deformations must not be exceeded. If, for example, we assume a stiffness in shear of 0.5 N/mm^2 over a 200-mm section of

Table 3: Mechanical data for a typical structural adhesive, which can be used for computer modelling purpose.

Stress	Temperature	Stiffness		Strength
		Shear	Compression/ Tension	Shear
Constant static, exposure period 3 years	23°C	0.5 MPa	–	0.16 MPa
	70°C	0.1 MPa	–	0.11 MPa
Quasi-static, 60 mm/min.	23°C	0.7 MPa	4 MPa	2.5 MPa
Dynamic, 10 Hz with 1% displacement amplitude	23°C	1.5 MPa	7 MPa	–
	90°C	0.8 MPa	4 MPa	–
	−40°C	13 MPa	56 MPa	–
Dynamic, 50 Hz with 17% amplitude, up to 10^8 cycles	30 – 40°C	1.2 MPa	–	0.2 MPa

an adhesive layer 15 mm in width and 4 mm in thickness, the spring constant for shear can be calculated as follows:

$$k_{Shear} = \text{Stiffnes in shear} \cdot \frac{\text{Surface to be bonded}}{\text{Thickness of adhesive layer}} =$$

$$= 0.5 \cdot \frac{200 \cdot 15}{4} \frac{N}{mm} = 375 \frac{N}{mm} \qquad (11)$$

The spring constant for compressive/tensile stresses is determined in exactly the same way.

Modelling with volume elements

Volume elements are well suited for modelling the adhesive layer since they allow tensile and compressive stresses to be represented with great accuracy. The optimum compromise between modelling complexity, computing time and accuracy results from using at least one quadratic volume element (Fig. 19a) or two linear volume elements (Fig. 19b) over the whole of the adhesive layer thickness. It is important to model the adhesive layer at the finest possible resolution, so that its deformation behaviour can be accurately represented. The more elements are used, the better our understanding of the distribution of stresses within the adhesive layer. If there are no restrictions on modelling complexity or computing time, it is generally advantageous to increase the number of elements.

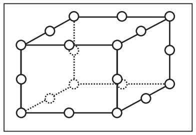


Abb. 19a: Quadratic volume element

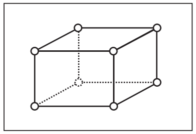


Abb. 19b: Linear volume element

Selecting and working with adhesives

This chapter looks at the question of selecting the right adhesive for the job. The key to a successful adhesive bond – apart from choosing an adhesive with the required performance characteristics – lies in correct application techniques. The adhesive develops its full strength only during the assembly process, so that at least as much careful attention needs to be paid to correct application procedures as to the mechanical properties of the product itself.

Mechanical performance data

The mechanical performance data for all elastic adhesives are broadly comparable. Once the right joint configuration has been established, it is then a matter of selecting an adhesive that is (1) suitable for the materials to be joined and (2) simple and economical to apply. To achieve this it may be necessary to set up a new production line that is specially geared to the adhesive bonding process. Alternatively, that process can be integrated into an existing manufacturing operation. The crucial point is to design the production process in such a way that the final strength properties of the adhesive and the adhesive bond are exactly and consistently reproduced in every part assembly processed. The application characteristics of the adhesive, together with the whole surface preparation sequence (cleaning, degreasing, priming), therefore have a very important role to play.

The range of choice in elastic adhesives

One- and two-part systems

Reactive adhesives for elastic bonding are available as two-part systems, based on polyurethane, polysulphide or silicone compounds, or one-part systems (see below, p. 64 f.). The latter

are widely preferred on the grounds that they are easier to use and give more consistently reliable results (less room for operator error). With two-part systems, it is necessary to check and monitor the accuracy of the mixing and dosing processes and the quality of the adhesive bond, and the additional cost and effort involved can only be justified in applications where the joint has to attain a high initial strength very quickly.

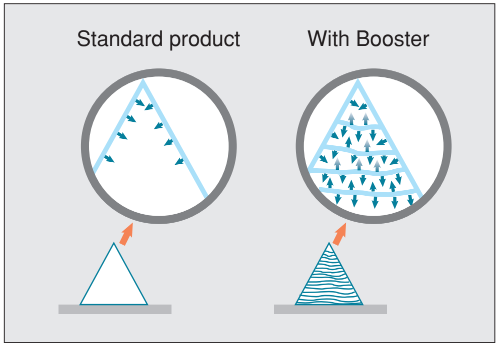
The vast majority of one-part elastic adhesives are moisture-curing polyurethanes, which combine high flexibility and elongation at break with good strength characteristics. Also available are sealants of lower adhesive strength. These are based for the most part on moisture-curing polyurethanes, silicones or silane-terminated polymers (hybrids/MS), and do not attain the same high mechanical strengths or exhibit the same durability as polyurethane adhesives. Because of their excellent adhesion and the wide variety of different mechanical properties and working characteristics, polyurethanes are unquestionably the most important class of adhesives for elastic bonding applications. The discussion that follows therefore confines itself exclusively to these products.

Polyurethanes

Polyurethanes are based on isocyanate-terminated prepolymers that react with atmospheric moisture. The isocyanate groups combine with water to form a polymer (polyurethane) by the elimination of carbon dioxide. Through the use of so-called latent hardeners, which are added to one-part adhesives, this elimination of gas can be avoided. In this case, water or heat separates the latent hardener and liberates a component that then reacts with the isocyanate prepolymer to form a polymer without the elimination of gas.

The start of the reaction is signalled to the user by the formation of a skin on the adhesive, which marks the point from which proper wetting of the substrate can no longer take place, and satisfactory adhesion can no longer be

Fig. 20: The effect of a cure accelerator (Booster) on adhesive cure



achieved. The cure process becomes progressively slower as the depth of the adhesive layer increases; adhesive joints made with this type of product should not exceed 20 mm in width in order to ensure that full cure is attained within 14 days.

Shear modulus 1 – 10 MPa

All these adhesives have been specifically designed for elastic bonding, and as such they have a shear modulus which is generally in the range 1 – 3 MPa. Special formulations for modular construction systems achieve shear modulus values of up to 10 MPa while still exhibiting an elongation at break in excess of 200%. The many different types of cold-applied standard adhesives are distinguished by application-specific characteristics such as sag resistance or ease of tooling and finishing.

Faster rate of cure

Strength development can be speeded up by the use of a *cure accelerator* or *Booster.* The addition of a cure accelerator to the adhesive has very little effect on the open or working time (i.e. the interval between application of adhesive and joint assembly), but results in significantly faster setting after just two hours (Figs. 20 and 21). Since the cure mechanism again depends on exposure to moisture, the system is not sensitive to incorrect dosages; full cure takes place sooner or later anyway, and any excess water eventually evaporates.

Fig. 22 (opposite): Strength development of polyurethane adhesives

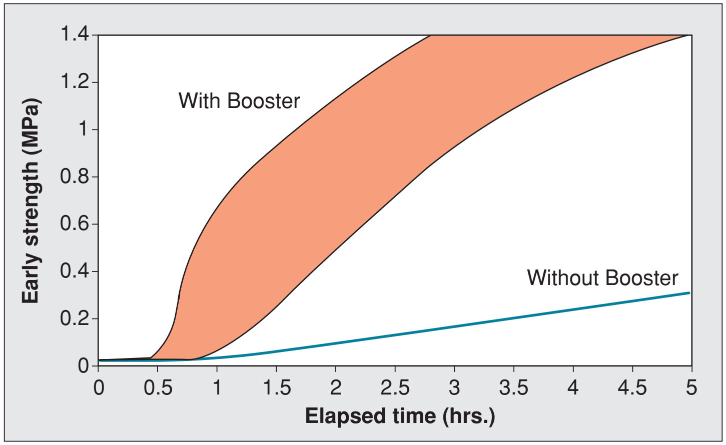
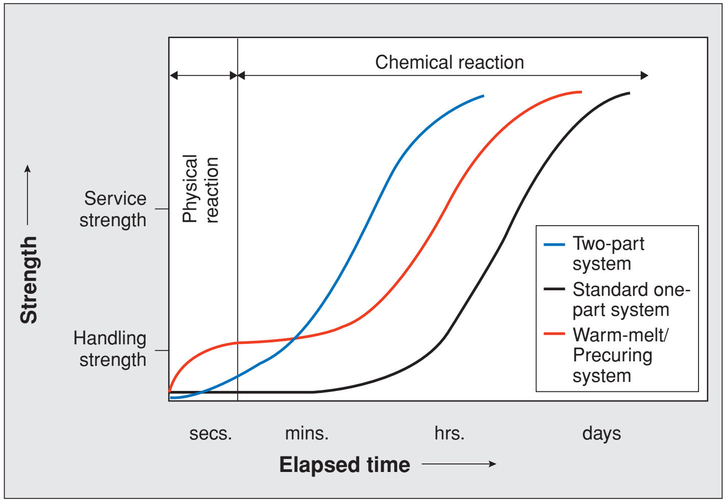


Fig. 21: Comparative rates of strength development with and without Booster

High early strength and sag resistance can be achieved by the use of *precuring systems* or adhesives that contain crystalline substances *(warm-melt systems)*. These adhesives possess excellent working characteristics when heated up, and for the most part exhibit high early



High early strength and sag resistance

strength and sag resistance very quickly after cooling down (Fig. 22). This means, for example, that an adhesive-bonded car windshield will not slip down after installation. Which in turn means that the vehicle can be despatched from the factory more quickly. With warm-melt adhesives, a handling strength of approx. 0.4 MPa is attainable five minutes after the bond is completed; tack-free and full cure times remain largely unaffected. In other words, the use of adhesives does not slow down the manufacturing process.

Short cure times can also be achieved by using two-part adhesives. These are based on isocyanates or prepolymers, and react with a second hydroxyl- or amine-based component. The speed of reaction can be adjusted here within broad limits and adapted to the specific application requirements. Table 4 gives a comparative overview of the different systems and their properties.

Adjustable speed of reaction

Table 4: Comparative performance data for elastic adhesives

Adhesive properties	Standard one-part products	Booster adhesives	Warm-melt/ Precuring systems	Hot-cure adhesives	Two-part adhesives
Open or working time (mins.)	5 – 45	15 – 30	5 – 15	Up to 60	0.1 to 60
Tack-free time (mins.)	10 – 60	n.a.	10 – 30	n.a.	n.a.
Resistance to sagging/slip-down	+/++	+	0/+	+	0/+
Depth of cure after 24 hours 1)	2 – 5 mm	Fully cured	2 – 5 mm	n.a.	n.a.
Handling strength after 4 hours (MPa)	0 – 0.2	> 1	> 0.4	n.a.	n.a.
Application temperature	Cold	20/80°C	60 – 80°C	Cold	Cold
Tensile lap-shear strength when cured (MPa)	1 – 10	1 – 3	3 – 5	2 – 5	2 – > 20
Specific product features	Easy to apply, minimal investment in application systems	Rapid rate of cure at room temperature	High early strength and good working characteristics, cures at room temperature	Rapid rate of cure above 100°C	Working and final characteristics adjustable within broad limits

n.a. = not applicable   0 = slight   + moderate   ++ high
1) 23°C/50% rel. humidity

Surface preparation

The most important factor in adhesive bonding is the condition of the substrate – the surfaces of the materials to be joined. Since adhesion takes place only at the interface between the workpiece and the adhesive, it is evident that surface preparation has a crucial bearing on the quality of the adhesive bond.

Treatment methods

The options for surface preparation and treatment are many and varied. They include simple cleaning of the surface, mechanical abrasion, the chemical alteration of the surface by pickling or phosphatizing, thermal processes such as flame treatment, as well as specialized physical-chemical techniques such as corona or low-pressure plasma treatments. In addition there are various kinds of paint systems and coatings, including primers and lacquers, which can often be used to provide a satisfactory substrate for adhesives. Glass surfaces need to be treated

Table 5: Typical surface treatments for common substrates

Material	Abrading/ Cleaning	Degreasing/ Activating	Priming	Remarks
Aluminium, anodized		x	x	
Aluminium, bare	x	x	x	
Steel	x	x	x	
Stainless steel	x	x	x	
Glass		x	x	UV protection
Glass with ceramic screen print		x		
Wood			x	Remove dust
ABS	x	x	x	
GRP	x	x	x	
PVC	x	x	x	
Polycarbonate	Seek advice from Technical Service Department			
Paint systems (depending on chemical composition)		x		

with a reactive cleaning agent or activator, in order to prevent the ingress of moisture below the adhesive layer.

Table 5 lists typical surface treatment options for a range of common substrates. It has been compiled with the emphasis on simple production methods, which do not require investment in expensive technology or engineering systems. The reference to UV protection has to do with the fact that when clear glass is adhesive-bonded, the actual bond face needs to be shielded against UV radiation by some form of opaque mask or covering. In practice, this is normally achieved by applying a ceramic screen-printed border to the glass that is both decorative and impervious to UV radiation. Suitable methods of surface preparation for mass-production applications must be discussed and coordinated with the technical service department of the adhesive manufacturer. Adhesive manufacturers have established appropriate treatment methods for the main substrates encountered in industrial production work, and have prepared step-by-step working instructions for users. They are therefore in a position to offer their customers the best professional advice.

Adhesive application

Triangular bead

Adhesives of stiff, paste-like consistency are normally applied in the form of a triangular bead, which is then compressed to its final design height (generally half of its original height) when the two substrates are brought together under pressure. The correct bead configuration is obtained by extruding the adhesive through a nozzle with a triangular cutout in the side, which is held perpendicular to the surface. It is important to ensure, either at the design stage or by taking appropriate measures at the time of application, that the desired thickness of adhesive is maintained. Application in bead form ensures that the adhesive makes full contact with the substrate, wetting it completely and eliminating air pockets. And because the adhesive does not drip or “string”, it can also be applied to vertical and overhead surfaces. It is important to make sure that any solvents contained in primers or surface activators have fully evaporated prior to application of the adhesive. The condition of the substrate must also be precisely known.

Open time and tack-free time

The open or working time is stated in the technical data sheet for the product concerned, and must never be exceeded. It should also be borne in mind that the stated tack-free or skinning time is only applicable for the standard climatic conditions specified in the data sheet. At higher temperatures and/or relative humidity levels, the tack-free time is significantly shorter.

For large production runs and automated application via industrial robots, the applicator nozzle must be cleaned at regular intervals to ensure a consistently clean finish. It is also advisable to maintain a constant working viscosity – which is not dependent on ambient temperature and humidity – by regulating the temperature of the delivery hoses, thus ensuring the total reproducibility of the application process.

Application equipment and systems

The choice of adhesive determines the type of application equipment required. For most industrial applications pump-operated applicator systems are used, designed to pump the adhesive direct from bulk drums at relatively high working pressures. Systems for use with hot-applied adhesives need to be equipped with heated follower plates, hoses and guns. For automated application, additional dispensing units are necessary to meter the exact quantity of adhesive required for each application.

The working range of these pumped applicator systems is determined by the length and manoeuvrability of the hoses. For application by hand, users have a choice of cartridges or foil-wrapped portion packs (Unipacs), which are dispensed with a standard hand-operated skeleton gun (cartridges) or solid-barrel cartridge gun (Unipacs). Compressed air and battery-operated models are also available. Hot-applied adhesives for application by hand are preheated to the required working temperature in special cartridge-warming ovens.

Elastic bonding in practice: A typical industrial application

“Cobra” tramcar

The new tramcars for the city of Zurich (type designation “Cobra”) are a good example of the latest developments in modern commercial vehicle engineering combined with the use of elastic bonding technology. The design team was given the following brief:

- Innovative and modern design
- Low-floor construction
- Low overall weight
- Low-cost, efficient production methods
- Low cabin noise levels.

In order to meet these requirements, the designers developed a modular hybrid construction system where a series of prefabricated and finish-lacquered modules – driver’s cab, sidewall panels, windshield, roof and floor sandwich panels – are adhesive-bonded to the aluminium body of the car (Figs. 23 and 24). Table 6

Abb. 23: Adhesive-bonded windshield

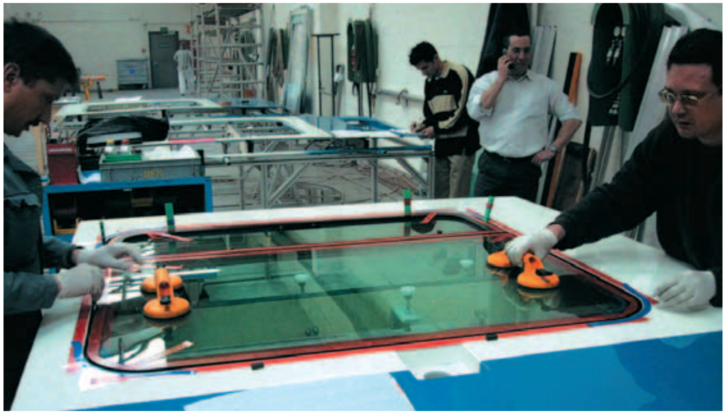


Abb. 24: Installation of window glass in sidewall panel

Module	Substrate material	Adhesive
Driver's cab	Glassfibre-reinforced plastic (GRP) Laminated safety glass (LSG)	Cure-accelerated adhesive (Booster) One-part polyurethane structural adhesive
Sidewall panels	GRP/Toughened safety glass (TSG)	One-part polyurethane structural adhesive
Roof sandwich panels	Aluminium, primed	One-part polyurethane structural adhesive
Floor sandwich panels	Aluminium, primed	One-part polyurethane structural adhesive

Tab. 6: Substrates and adhesives

gives details of the most important adhesive applications.

The use of elastic bonding technology in the form of one-part polyurethane adhesives has enabled the design and engineering team to realize its vision for a hybrid low-floor tramcar in a highly efficient and cost-effective production process. The benefits of elastic bonding include:

Benefits of adhesive bonding

- Bonding and sealing in a single operation
- Joining of different materials and different types of surface finish (full paint system, primer coat, etc.)
- Ability to accommodate manufacturing tolerances (gap-filling properties)
- Distortion-free connections with no markthrough
- Uniform distribution of stresses under heavy loading
- Excellent damping properties and improved ride comfort.

As soon as development work began on the “Cobra” tramcar, attention was focused on optimizing the stiffness and strength of the structure. Computer-based FEM techniques were used to calculate shear, compressive and tensile stresses under a variety of different load conditions. The decoupled spring elements are 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 the case of vehicles – such as this one – which are built using hybrid construction methods, the dimensioning of the adhesive joints is accorded top priority from the earliest development stage, since this is critical for the attainment of the necessary design strength (Fig. 25).

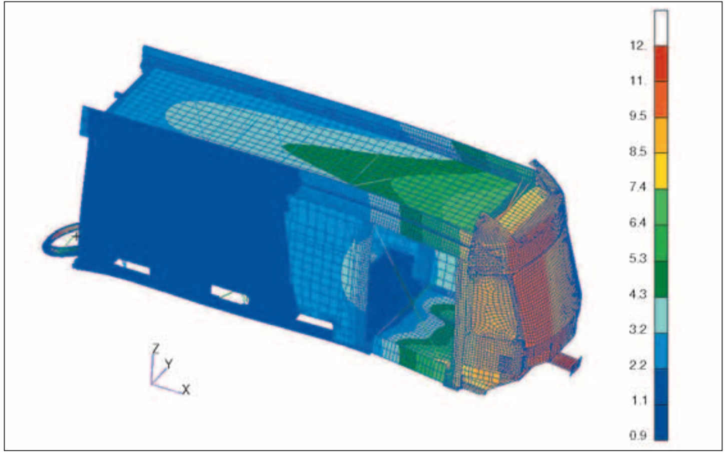


Abb. 25: Using FEM simulation to model global deformation in the “Cobra” tramcar when cornering (measurements in mm)

Slim-profile PVC window sash

Another example of the use of elastic bonding technology can be seen in the window industry. The window frame has to support the glass, and must be designed accordingly with adequate strength and rigidity. In order to make the stiffness of the glass contribute to the overall strength of the window assembly – just like direct glazing in the automotive industry – a new window system with the appropriate adhesive was developed. The result is a slim-profile PVC window sash that is able to dispense with the usual steel reinforcement. The designer's aim was achieved by using a warm-applied adhesive that is injected into the narrow gap between frame and sealed glazing unit (Fig. 26). By injecting the adhesive with a fine nozzle (0.5 mm diameter) under high pressure (200 bar), the sash frame and the edge of the glazing unit effectively become a single structural assembly. When the adhesive cools down, it quickly attains sufficient handling strength for the production process to be com-

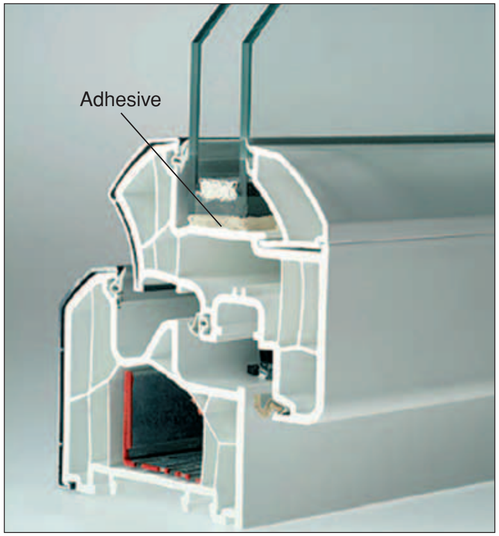


*Abb. 26:
Sealed unit and sash profile – joint detail*

No production delays

pleted without delay. The adhesion promoter is integrated into the extruded section of the PVC profile, so that the entire manufacturing process can be largely automated.
This process results in a window that offers many advantages both to the manufacturer and to the end user:

- Production can be automated
- Larger visible glass area, modern styling
- Reduced window weight, savings in raw materials
- Easier to open and close, because stiffer sash assembly resists twisting and racking
- Improved thermal properties
- Increased security against break-ins.

Disassembly and repairs

Tools for removing

Repairs to elastic-bonded assemblies are easily carried out with the aid of modern tools designed to facilitate disassembly. A variety of such tools are now available on the market. Windshields are removed either with a special cutting wire or with trimming knives powered by compressed air or electricity (Fig. 27). Depending on the type of vehicle, these knives are used with special offset blades designed to cut cleanly through the old adhesive without damaging the window surround.

*Abb. 27:
Removing an adhesive-bonded windshield*

The side walls of buses or rail vehicles occasionally need to be replaced following an accident or an act of vandalism. To facilitate repairs the side wall assemblies are often made up of several sections, each of which can be removed separately. Since elastic adhesives are applied in layers several millimetres thick, an electric trimming knife can safely be used to break the joint without damaging the substrate.

Separate sections to facilitate repairs

After cutting away the damaged section, it is not necessary to remove all traces of the old adhesive. Treated with an activator, the old adhesive layer provides an excellent substrate for the new adhesive, and a triangular bead of fresh adhesive is simply applied to the cut face of the original bead. Leaving the remains of the old adhesive layer in place also minimizes any risk of damage to the paint finish. It is advisable to try the new component in position first before applying the adhesive, adjusting it for fit and marking its precise position with strips of tape.

The surface of the new side wall is then cleaned and primed in accordance with the adhesive manufacturer’s instructions. Ideally, the side wall should be positioned over the adhesive and pressed into place with the aid of suction clamps, which can then be left in position to hold the assembly while the adhesive is curing.

Assuming the components have been painted prior to bonding, down time due to repairs is reduced to a few hours. Another time saving aspect of this type of repair is that it involves no application of heat to the components, so that the removal and replacement of other heat-sensitive components, such as insulation materials or electric cables, becomes unnecessary.

Quality assurance

Particular attention needs to be paid to establishing an effective system of quality assurance for adhesive connections. Non-destructive test methods based on ultrasound, X-rays or the measurement of electrical or thermal conductivity are of only limited value in practice. Specific data on adhesion cannot be obtained by these methods. This chapter examines the issue of quality assurance from a practical point of view. Many years of experience have shown that only a quality assurance system that takes account of the specific features of adhesive bonding technology can produce consistently satisfactory results over an extended period. The proposals outlined here should be viewed as a kind of general checklist, to be adapted to the specific requirements of each manufacturing environment.

Continuous monitoring and checking

An effective quality assurance system for elastic adhesives depends on continuous monitoring and checking of all quality-related parameters. If these are maintained within the prescribed limits, then the quality of the adhesive connection is guaranteed, with little or no need to supplement these control measures with time-consuming and costly destructive testing. The overall cost of quality assurance is therefore kept down to a commercially acceptable level.

Table 7:
Factors affecting the quality of an elastic adhesive bond

Adhesive	Selected to suit the requirements of the production cycle and the service stresses to which the finished assembly will be subjected
Substrate	Consistency of composition and surface condition
Surface preparation	Selected to suit the requirements of the production cycle and the service stresses to which the finished assembly will be subjected
Application parameters	Working within the specified time limits (open time), taking account of temperature and relative humidity levels
Joint design	Adhesive-friendly joint design, dimensioning of joints to suit functional requirements of finished assembly
Staff training	External (e.g. IFAM, Bremen) or internal training courses organized in conjunction with adhesive suppliers

As Table 7 shows, the task of assuring the quality of the bonded assembly begins at the project stage and does not end until production ceases. A typical quality management programme for adhesive applications is set out in Table 8. This model has been adopted with very satisfactory results in many areas of the manufacturing industry.

Project study	Construction of prototype	End of test phase	Series production
Design and construction adapted to adhesive technology and assembly methods	Checking and specifying correct method of substrate preparation in consultation with adhesive and paint suppliers	Evaluation of test phase, making any design changes that may be indicated	Implementation of quality assurance system
Dimensioning and configuration of adhesive joints based on existing codes of practice and design data	Construction of prototype based on design criteria for adhesive bonding. Adhesive supplier (applications engineer) to advise where necessary	Preparation of a production and quality assurance manual for adhesive bonding applications (taking account of the key application parameters temperature and relative humidity)	Periodic refresher courses and further training for personnel (corporate training programme)
Appointment of an in-house adhesives specialist to liaise between departments on all aspects of adhesive usage	Specifying type and scope of repair works	Training of assembly personnel in use of adhesives	Introduction of activities aimed at raising quality standards (e.g. quality awareness groups)

Table 8: Quality-related activities over the life of a project

In-house adhesives specialist

In commercial enterprises that use adhesives in series production, a sound working knowledge of adhesive technology is generally confined to a few individuals in technical departments. The policy of training one technician as an in-house adhesives specialist has proved to be an efficient solution to this problem. This person is also able to coordinate all aspects of adhesive usage for the project as a whole and act as a neutral adviser to the individual departments concerned. Table 9 is intended as a guide to the preparation of a quality assurance concept. The scope and frequency of the test regime will need to be adjusted to the scale of the project and the available technical and manpower resources.

Area of responsibility	Checks and controls	Department/ Person responsible
Ensuring consistent quality of substrate	Specification (name, brand, grade, supplier, chemical composition, etc.)	Design and Engineering
	Contractual agreements specifying quality and condition of substrate (duty to inform in event of changes)	Purchasing
	Checks on incoming deliveries (name, brand, grade, product characteristics)	QA
	Correct storage (temperature, humidity, prevention of soiling, first-in first-out stock rotation)	QA/Logistics
Preparation of substrate	Specification (mechanical surface preparation, chemical products, type of application, processing schedule)	Design and Engineering/ Adhesives technician/ Adhesive supplier
	Checks on incoming deliveries (name, brand, grade, visual inspection of packs, product characteristics)	QA
	Correct storage (temperature, humidity, prevention of soiling, use of stock by expiry date)	QA/Logistics
	Subjective checks for visible defects in primers, etc. (cloudiness, sedimenting, thickening, etc.), plus checks on expiry date	QA/Foreman
	Periodic checks on correct application procedures (method of application, observance of recommended drying times, correct handling of primed components prior to assembly, etc.)	QA/Adhesives technician
Application of adhesive	Checks on incoming deliveries (name, brand, grade product characteristics, visual inspection of packs, periodic adhesion tests)	QA
	Correct storage (temperature, humidity, conditioning of stock to room temperature, use of stock by expiry date)	QA/Logistics
	Subjective checks for visible defects in adhesives (changes in consistency, flow behaviour, etc.), plus checks on expiry date	QA/Foreman
	Periodic checks on correct application procedures (method of application, observance of specified open times, correct joint assembly sequence, waiting times prior to further processing, etc.)	QA/Adhesives technician

Table 9: Checklist for monitoring adhesive applications

Most people, no matter how well-versed they are in technical matters, are instinctively sceptical about the concept of adhesive bonding. Those who work in the traditional mechanical fastening trades are especially difficult to convince: Having worked hard to acquire an exacting skill, they are naturally reluctant to accept that it can be replaced by such a seemingly basic and simple joining method. Once it has been introduced, however, adhesive bonding is quickly accepted, and the initial scepticism gives way to a confidence that can become complacency: In the absence of a proper quality assurance system, correct application procedures may be neglected, with the possible risk of joint failure at a later date. In fact the professional use of adhesives should not be regarded any differently than the exercise of other traditional industrial skills such as welding or the application of paint coatings. The only real difference lies in the less sophisticated quality of skills training provided for operatives. The successful use of adhesives presupposes a level of technical knowledge that designers, engineers and assembly personnel do not automatically possess. Hopefully this deficit can be made good in the not-too-distant future by persuading technical colleges and vocational training establishments to put adhesive bonding technology on the syllabus. In the meantime, the manufacturing industry must continue to fill the gap as best it can with specialized courses and internal training schemes organized in conjunction with adhesive suppliers.

More skills training needed

Long-term serviceability

The long-term serviceability of an adhesive connection, i.e. its ability to continue functioning effectively throughout its design life, is a vital prerequisite for the successful use of adhesives. While adhesive bonding as such is one of the oldest joining methods known to man, the use of synthetically based structural adhesives is still relatively new. The oldest epoxy resin products date back no further than the 1950s. Tests carried out on bonded assemblies after a service life of more than 20 years yielded strength values that differed only marginally from the original values measured at the time of application. The long-term durability of a correctly executed adhesive joint is conclusively demonstrated by tests such as these.

Determining factors

Ageing

Elastic adhesives are organic products, and as such are subject to ageing in one degree or another. The design of the adhesive joint has to take account of this complex process. In this chapter we shall consider the various factors that have a long-term impact on ageing. The production conditions needed to ensure an effective and durable adhesive connection were discussed above in the chapter *Selecting and working with adhesives*. Table 10 contains a summary of the principal ageing factors encountered in practice.

The effect of chemical substances

Adhesive joints are exposed to attack from many different chemical products. In most cases this means short to medium-term contact with water,

Type	Subgroup	Examples
Chemical exposure	Water	
	Chemicals	Salt water, detergents/detergent solutions, fuels, gases
Radiation	IR (Temperature)	
	UV	
	Other	
Mechanical stress	Elastic moduli	
	Joint geometry	
Substrates	Permeability to radiation	Glass, plastics
	Susceptibility to stress cracking	Acrylic, polycarbonate, polystyrene, ABS, etc.
	Dimensional stability	GRP (unsaturated polyester), wood and wood panel products
	Diffusion processes	

Table 10: Ageing factors affecting durability of adhesive joints

aqueous solutions or fuels. The following factors are of critical importance here:

- Duration of exposure and exposure temperature
- Type and concentration of chemicals
- Joint design.

Resistance

Adhesives are resistant to most of the above-named substances for a limited period of time, and generally speaking they can safely be used provided joints are designed in accordance with normal good practice (such as taking steps to prevent permanent exposure to condensation in the case of window glass). When bonding metals with adhesives, the whole question of corrosion protection needs to be very carefully considered. The purpose of such protection is to prevent the spread of corrosion beneath the adhesive layer, which eventually leads to failure of the joint (so-called bondline corrosion). Elastic adhesives are particularly well suited to this type of application, since they are fully compatible with a wide range of corrosion protection systems.

> As a general rule, the use of adhesives is not recommended where they are likely to be constantly exposed to chemical products (apart from water and neutral aqueous solutions).

In cases where adhesive joints may be exposed to chemical attack, it is essential to seek the advice of the adhesive manufacturer.

The effect of temperature change

Prevent overheating

The temperature resistance of elastic adhesives is low in comparison to mechanical fastening techniques. It is comparable with the temperature resistance of thermoplastics and thermoplastic paint systems, and is adequate for most applications under normal stress conditions (i.e. outdoor applications with no exposure to any additional or concentrated heat source). However, the possible effects of overheating of the adhesive (in the event of fire, for example) must be taken into account at the design stage. If there is any risk that the failure of an adhesive joint as a result of overheating could cause personal injury or collateral damage, additional mechanical safeguards must be incorporated into the design.

Effects of UV radiation

Ultraviolet radiation is a component of normal sunlight. This high-energy radiation is the primary cause of damage to the exposed surfaces of organic materials. Although the surface of elastic adhesives and sealants is not significantly degraded by UV exposure, so that their long-term functional effectiveness is not impaired, additional protective measures are necessary when bonding transparent or translucent materials (see section on *Transparent substrates* below).

Mechanical stresses

Tests with prototypes

Excessive mechanical stressing of the bonded substrates causes irreversible damage to the adhesive layer. Stress levels should therefore not exceed the maximum safe values determined through dynamic and static tests. The stresses that actually occur in service cannot always be precisely predicted. Elastic adhesives exhibit a deformation behaviour that is easily measured. It is therefore 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 the design engineer to quantify the stresses accurately, so that he can if necessary modify the adhesive geometry or use a product with a higher modulus.

Transparent substrates

UV protection

Glass and plastics, both transparent and translucent, allow light and UV radiation to pass through them. When adhesives are used with these substrates, therefore, the interface between adhesive and substrate must be shielded to protect the boundary layer of the adhesive against possible radiation damage. This boundary layer is extremely vulnerable; all that is required is the destruction of the outermost layers of molecules for adhesion to be significantly impaired. Alongside various recognized ways of masking the joint with a suitable opaque material (ceramic screen-printed border, cover trims, opaque paints), some manufacturers recommend the use of a black primer as the sole form of UV protection. However, long-term field trials carried out in Florida and South Africa on vehicles with adhesive-bonded window glass have shown that pretreatment with a black primer gives less effective long-term UV resistance than the primerless installation of auto glass with integral UV protection (ceramic screen-printed border with a light transmittance value of 0.1% or less).

Stress cracking

Thermoplastics

Thermoplastics are characterized by the presence of internal stresses which are due in part to the manufacturing process (extrusion or thermal forming of sheet materials). When these materials come into contact with chemicals (especially solvents), cracks may form. This phenomenon is known as Environmental Stress Cracking (ESC). However, cracking can also occur in the absence of any discernible chemical contact, as in the case of the hairline cracking to which the plastic windows of aircraft are prone. This group of products should be bonded with adhesives only if the following conditions are met:

- The adhesive manufacturer’s recommendations regarding the choice of products and the correct method of surface preparation must be followed.
- Only stress-free (tempered) plastic components may be installed in this way.
- The plastic components must be installed without introducing localized stresses, and adequate provision must be made to accommodate movement resulting from thermal expansion (thick-layer bonding using a low-modulus adhesive).

Glass-fibre-reinforced plastics (unsaturated polyester GRP)

Material-induced shrinkage

Sheets or components made from glass-fibre-reinforced polyester undergo a process of shrinkage during polymerization (curing), which continues for several weeks. Components made from this material should not be adhesive-bonded too soon after manufacture: The ongoing shrinkage process would place the component – and consequently the adhesive bond – under a constant stress. This, combined with normal service stresses, could lead to premature bond failure. Alternatively, glass-fibre components can be heat-treated for a few hours to stabilize them – a process known as tempering. Adhesive bonding of GRP materials should therefore be restricted to tempered components or components that have been stored for a period of time.

Tempering or conditioning

Wood and wood products

Wood readily expands and contracts in response to changes in its moisture content. Wood and wood products – including panel products and plywood – shrink when they lose moisture. To prevent the kind of movement-induced stresses referred to in the previous section, only wood with a balanced moisture content should be selected for adhesive bonding.

Check moisture content

Diffusion processes

Thermoplastics and paint systems that behave like thermoplastics are quite often soluble in organic solvents. Many adhesives contain small amounts of such solvents or plasticizers. The diffusion of these products towards the boundary layer can lead to a softening of this layer at the adhesive interface. If the joint is then subjected to stress, the adhesive bond may fail. Since the diffusion process takes place very slowly, months may elapse before the damage manifests itself. One answer is to use a thermosetting plastic; alternatively, the user should seek the adhesive manufacturer’s advice on an appropriate method of surface preparation.

Safety at work and environmental safeguards

Potential risks

Adhesives and the products used to prepare the surface for adhesive bonding are all chemical products, and as such they may contain substances that are potentially harmful to human health and to the environment. The potential risks of adhesive use, as compared to conventional mechanical joining methods, are frequently exaggerated, while the fact that other joining techniques are also subject to health and safety legislation is generally overlooked. Welders, for example, are required by law to protect themselves against the physical absorption of harmful chemical substances, such as the gases and dusts given off during the welding process.

As the renowned physician and naturalist Paracelsus postulated back in the Middle Ages, the definition of a toxic substance is essentially a matter of dosage. If the dose is small enough, it poses very little risk to human health. This principle is central to government health and safety legislation aimed at safeguarding people against the inhalation of harmful substances. The so-called *occupational exposure limit* is the threshold limit that defines the maximum concentration of an airborne substance to which a worker may be continuously exposed for eight hours a day, five days a week, without experiencing any adverse impact on his or her health. These threshold limits are based on a combination of toxicological studies and practical experience, and are subject to constant review as more scientific data become available.

Occupational exposure limit

It is most important, therefore, to develop good working practices for adhesive bonding applications so that physical contact with these substances is avoided as far as possible. The clean

Avoid physical contact

working environment and careful, methodical workmanship that are required for successful adhesive bonding go some way towards meeting this objective.

Statutory requirements

The statutory requirements relating to the use of adhesives are many and varied, with considerable differences from one country to the next. It is beyond the scope of this handbook to provide a detailed catalogue of these rules and regulations. The discussion will therefore be confined to selected practical aspects that can be readily incorporated into a responsible safety concept. The existing legislation relates specifically to the following areas:

- Storage and transport
- Adhesive application
- Use of the finished assembly
- Waste disposal.

Safety data sheet

Users with little experience of handling chemicals generally face a whole series of new problems, and for this reason they are often reluctant to use adhesives. In order to address the concerns of these users the government therefore requires adhesive manufacturers to compile a safety data sheet incorporating all the relevant statutory requirements.

The safety data sheets issued for different countries do not follow a uniform pattern, but they do conform broadly to the European standard safety data sheet as defined in EC Directive 91/155/EEC. This document contains sixteen sections, the contents of which are briefly summarized in Table 11. However, all the data contained in the published safety data sheets are based on a worst-case scenario. In practice, provided the products are handled with proper care and attention, the potential risks are generally less serious than they are assumed to be for the

	Subject	Contents
1	Labelling of substance/preparation and manufacturer’s designation	Proprietary name, intended use, manufacturer’s name and address
2	Composition/Information about constituents	Chemical description, hazardous constituents (incl. Chemical Abstracts number, concentration hazard symbols, risk and safety phrases)
3	Potential hazards to human health and the environment	Designation of hazards, special hazard warnings
4	First-aid measures	General advice, action to be taken following inhalation, skin contact, eye contact, ingestion
5	Action in case of fire	Suitable extinguishing agents, special hazards posed by the product itself or by gases and vapours released during combustion, special protective equipment needed for fire-fighting, additional recommendations
6	Action in the event of accidental release	Precautionary measures designed to protect exposed persons, environmental safeguards, clean-up procedures
7	Handling and storage	Safety measures designed to prevent fire and explosion, storage specifications for bulk/mixed storage, additional storage recommendations
8	Limiting exposure and personal protective equipment	Constituents that need to be monitored in terms of their maximum workplace concentrations, personal safety equipment (respirators, gloves, goggles, protective clothing)
9	Physical and chemical properties	Appearance, safety-related data
10	Stability and reactivity	Conditions to be avoided, dangerous reactions, thermal degradation and hazardous decomposition products
11	Toxicological data	Sensitization, known effects of human exposure (in cases of skin or eye contact, inhalation or ingestion)
12	Ecological data	Information on possible environmental hazards (contamination of water, soil and air)
13	Disposal of waste	Disposal of product and soiled packaging
14	Carriage and movement of goods	Classification for transport by road, rail, air and sea
15	Legal requirements	Labelling in accordance with national and international regulations (e.g. EC Directive 88/379/EEC on hazardous substances, toxicity classification, water pollution classification, etc.)
16	Miscellaneous points	

Table 11: Contents of European standard safety data sheet on the correct handling of adhesives, as defined in EC Directive 91/155/EEC

purposes of these publications – and certainly they are perfectly manageable.

Some practical pointers to the safe use of reactive one-part elastomeric adhesives

Elastic one-part adhesives can broadly be classified in terms of the following chemical compounds:

- Polyurethanes
- Silicones
- Modified silicones.

Polyurethanes are widely used as industrial adhesives because of their excellent plasto-elastic properties, while silicones and modified silicones are primarily used as sealants and adhesives in the construction sector. Table 12 lists the various constituents of these products that may represent a health risk, together with the critical exposure periods.

Table 12: Constituents of elastic adhesives that pose a potential health risk

Product basis	Potentially harmful constituents	Effects on human health	
		Adhesive users	**End users of bonded assembly**
Polyurethanes	Isocyanate monomers, solvents, plasticizers	Provided they are used correctly, elastic one-part polyurethane products give off no measurable emissions of monomers at room temperature (in some cases minute quantities of solvents may be emitted over a period of several days).	No known adverse effects, provided the assembly is used in accordance with the adhesive manufacturer's recommendations. Many products are also approved for use in contact with foodstuffs.
Silicones	Cross-linking agents, plasticizers, solvents	During the hardening process, some reaction by-products such as acetic acid, amines, oximes, etc. may be released, depending on the cure mechanism.	No adverse effects in normal use. Some products are also approved for use in contact with foodstuffs.
Silan-terminated systems	Cross-linking agents, plasticizers, solvents	Small amounts of methyl alcohol are released during the hardening process.	No adverse effects in normal use, no known approvals for use in contact with foodstuffs
Primers, etc.	Isocyanate monomers, cross-linking agents, solvents, plasticizers	Until the product has fully hardened, significant amounts of solvents and small amounts of reaction by-products or isocyanate monomers are emitted.	No adverse effects in normal use

Protection against emissions

Primers contain large amounts of solvents, varying between 50% and 99%, depending on type and cure mechanism. An effective extractor system must be installed in the workplace to draw off the emissions (fumes, etc.) associated with the use of these products.

Elastomeric adhesives, unlike hard-setting adhesives, can be applied over primer or paint systems that are necessary to protect components against corrosion. Minor adjustments to the assembly process often make it possible to restrict the amounts of chemical substances released during application to negligible levels. Table 13 lists various methods of surface preparation and treatment designed to reduce such emissions to a minimum.

Provided the products are used as directed and all the necessary precautions are taken, any risk to the health of production staff and end users can effectively be discounted.

Table 13: Methods of minimizing emissions when working with adhesives

Method	Substrates	Remarks
Use of precoated substrates	Sheet metal (coated coil)	Depending on the type of application, coil stock can be supplied with a coating to one or both sides. The stock can then be painted on one or both sides with a primer or finish lacquer to aid adhesion.
	Metals (precoated individual components)	Many ferrous metals are coated with a weldable anti-corrosion primer before they are used for industrial construction purposes. Since adhesives bond well to these primers, the need for further surface preparation is largely eliminated.
Physical methods of surface treatment		
Flame treatment	Polyolefins such as polypropylene, etc., together with many other plastics	Simple, fast process, but not suitable for manual application
Corona treatment	See above	Somewhat more time-consuming than the above process. The ozone produced during the electrical discharge must be extracted from the workplace.
Fluorination	See above	Relatively costly treatment method, and therefore uneconomic except for small components

Checklist for the use of elastic adhesives

The following checklist identifies the most important factors affecting the quality of an elastic-bonded joint and is intended as a guide to the correct use of adhesive bonding technology.

1. Function of adhesive joint
☐ Transference of forces
☐ Sealing and weatherproofing
☐ Sound absorption
☐ Insulating
☐ Accommodating dimensional tolerances

2. Substrates
☐ Material composition: …
☐ Name/Brand/Grade/Supplier: …
☐ Surface condition: …
☐ Special features (e.g. presence of release agents): …

3. Stresses
☐ Tensile
☐ Shear
☐ Static
☐ Dynamic
☐ Peeling
☐ Chemical (UV radiation, moisture, water, chemical media)
☐ Thermal (service temperature range)

4. Application
☐ Cleaning/Surface preparation and priming
☐ No. of units to be bonded
☐ Production cycle times
☐ Application equipment (applicator guns, pump units, etc.)
☐ Early strength requirements (for handling and further processing, dispatch, etc.)

5. Quality assurance
☐ Detailed process specification
☐ Adhesion
☐ Other tests: …
☐ Training of production staff

Future outlook

In its present form, elastic bonding is a proven fastening technology whose advantages over traditional fastening methods have made it an indispensable tool in many sectors of manufacturing, including the car and commercial vehicle industry, shipbuilding and the production of appliances and components.
Our understanding of material surfaces and surface preparation has grown considerably in the last 25 years. The durability of adhesive-bonded joints has also improved, thanks to new research and observation of certain rules relating to joint design, stress calculation and good practice at the application stage. Some important development goals for the near future include:

Development goals

- General-purpose high-tack adhesives, which guarantee secure, reliable joints with little or no surface preparation
- Ecological surface preparation methods
- Adhesives with very fast cure/reaction times
- High-modulus elastic adhesives
- Multifunctional adhesives with specific add-on properties.

More efficient and cost-effective

In recent years the use of adhesives has grown exponentially. The fact that adhesive bonding is increasingly replacing conventional fastening techniques is also related to the wider availability of training opportunities. Elastic bonding offers innovative and inventive designers and engineers the chance to develop and implement new fastening and construction solutions that are technically efficient and commercially cost-effective.

Glossary

Acrylate adhesive An adhesive obtained from the polymerization of acrylic acid

Activator A chemical agent used to prepare surfaces for bonding

Adhesion The bonding of different materials (e.g. adhesive and substrate) by surface attachment

Adhesive Non-metallic substance that joins components together by forming an interfacial bond between them

Adhesive joint (bondline) The gap between two components that is to be filled with adhesive

Adhesive layer The layer of adhesive between two bonded substrates

Balanced moisture content The moisture content of a material when allowed to stabilize relative to ambient levels of atmospheric moisture

Bond face The surface of a component that is to be coated with adhesive

Bond or interface strength The force that is needed to separate an adhesive joint

Booster See “Cure accelerator”

Breaking stress The stress required to produce failure or fracture in a material

Cataplasma test The storage of test specimens at 70ºC and 100% relative humidity

Clamping The temporary securing of components in the desired position by mechanical means, with or without the application of pressure, while the adhesive is setting

Cleaner A chemical agent used to clean surfaces prior to bonding

Coefficient of expansion The factor that expresses the dimensional changes in a component as a function of temperature change

Cohesion Collective term for the various molecular forces that unite the particles of a body throughout the mass

Cross-linking The creation of a three-dimensional network through the formation of chemical bonds between molecular chains

Cure accelerators Substances that reduce the curing time of adhesives

Curing The setting or hardening of an adhesive as a result of physical or chemical reaction

Curing conditions The factors that influence the curing of adhesives, e.g. temperature, relative humidity, etc.

Cyanoacrylate adhesive Fast-setting reactive adhesive (popularly known as “superglue”) which cures on exposure to atmospheric moisture

Diffusion Here: The movement of gases and liquids through substances

Elastomers Elastomers are macromolecules with an open network structure which do not undergo plastic flow even at high temperatures approaching the point of chemical decomposition, but undergo reversible elastic deformation instead

Elongation at break The elongation that takes place before a material fails or fractures

Final strength The strength of an adhesive joint when the adhesive has attained full cure

Fracture energy The energy that is required to cause a material to fail or fracture

Handling strength The stage of strength development when the adhesive-bonded assembly can be handled and passed on to the next stage of processing

Heat resistance A material is said to be heat-resistant when it undergoes no changes as a result of exposure to a specified temperature over a certain period of time

Hooke’s law Hooke’s law describes the relationship between applied stress and strain in an ideal elastic solid body

Joint assembly The process of bringing the substrates together under light pressure so that the adhesive film is compressed to form the adhesive bond

Modulus of elasticity The modulus of elasticity describes the ratio of stress to strain in a rod under tension whose sides are unconstrained

Monomers The initial products of the adhesive, from which polymeric molecular chains are formed by chemical reaction

Non-sag properties The resistance of an adhesive to collapse or “slump” when extruded in bead form

One-part polyurethane adhesive A polyurethane adhesive supplied as a single premixed compound, which cures on exposure to moisture or heat

Open or working time The maximum period of time that may elapse between application of the adhesive or activator and assembly of the joint

Peel strength Resistance of the adhesive joint to forces that are concentrated in a narrow area at the extremity of the joint, thereby creating stress peaks in the adhesive layer

Poisson’s ratio Defined as the ratio of lateral contracting strain to the elongation strain when a rod is stretched by in-line forces applied to its ends, the sides being free to contract

Primer A special paint coating designed to improve adhesion between adhesive and substrate

Reactive adhesives Adhesives that cure or set when exposed to heat, moisture, radiation, etc.

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Sealant Substance that separates a joint from any medium to which it is exposed

Shear modulus Defined as the ratio of the shear stress to the shear strain in a body that undergoes simple angular deformation

Shelf life The period of time that may elapse between the manufacture of an adhesive and its use, subject to storage of the product under controlled conditions

Solvent An organic liquid that dissolves the base materials and other soluble adhesive constituents without effecting any chemical change

Substrates Solid layers that are to be joined together or are already joined together

Tack-free or skinning time The time between the application of the adhesive and the formation of a skin on its surface, after which point bonding can no longer take place

Tensile lap-shear strength The breaking strength of the adhesive bond joining two parallel surfaces 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 The breaking stress of a material under tension

Thermosetting resins Closely cross-linked macromolecules that do not undergo plastic deformation even at high temperatures

Thick-layer adhesive bonding An elastic bonding application where the thickness of the adhesive layer exceeds 3 mm

Transmittance The ratio of the intensity of a beam of light passing through a body to its original intensity

Viscosity The resistance to flow exhibited by fluids or paste-like substances as a result of internal friction

Wetting The ability of liquids to disperse themselves uniformly over solid materials

Wöhler chart The representation of the magnitude of a mechanical stress to cause failure as a function of the number of load cycles

Yield point The force that must be applied to a non-sagging medium in order to cause it to flow

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Sika was established in 1910 and today employs more than 10,000 people in 70 countries and 90 group subsidiaries around the world. Within its four core areas of technological expertise – sealing, bonding, damping and reinforcing – Sika concentrates specifically on the following sectors:

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