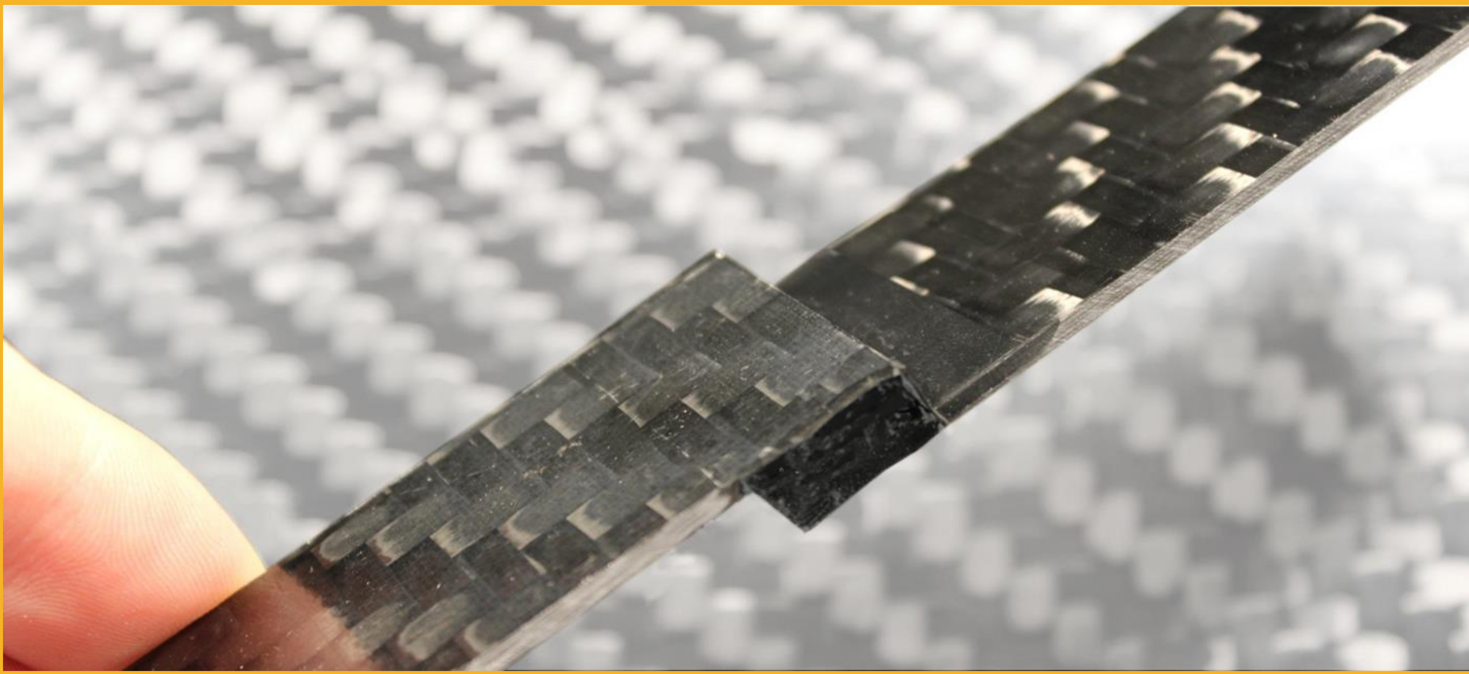

GENERAL GUIDELINE
Structural Bonding

JULY 2022 / VERSION 2 / SIKA SERVICES AG / MARKETFIELD ENGINEERING

Assembly bonding with SikaPower®, SikaForce® and SikaFast® adhesives

VALID UNTIL JULY 2027, UNLESS SUPERSEDED

BUILDING TRUST

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1 PREFACE

This general guide contains information, rules and recommendations for assembly bonding applications with Sika's structural adhesives, namely adhesives having high elastic modulus. The interested products include epoxy-based SikaPower®, polyurethane-based SikaForce® and acrylic-based SikaFast® adhesives. Because of the variety of applications and factors that affect the quality and the durability of adhesive bonds, the document does not aim to be exhaustive nor complete. Its goal is to provide practical guidelines and easy-to-access references to designers, engineers and applicators of structural adhesives. It is assumed that readers have starting knowledge of mechanics and material properties.

The following chapters illustrate the basics of structural assembly bonding and are specifically dedicated to: joint design (Chapter 2); adhesive properties and testing (Chapter 3); general criteria for selection and use of structural adhesives (Chapter 4).

This document is valid until the date stated on the front page or until a new version is issued. For more detailed information related to applications or products mentioned in this document, contact the Technical Department of Sika Industry.

2 JOINT DESIGN AND DIMENSIONING

The chapter illustrates the elementary principles of joint design with structural adhesives. Basic design guidelines are outlined for structural bonding and the given information applies in general, independently of the specific adhesive materials that are used.

2.1 INTRODUCTION

The advantages that structural adhesives offer over other types of fixations are achievable only if the joints are adequately designed. Generally, it is not reasonable to follow designing rules for e.g. welds and merely substitute weldlines with bondlines. In designing bonded joints, the basic characteristics of adhesives must dictate the joint design. In particular, the joint should be designed with the objective of minimizing stress concentration, because adhesive bonds act over areas and not single points or lines [1]. As an example, Figure 1 shows how a typical T-joint could be modified when switching from fillet welding to structural bonding, in order to allow for distribution of stresses over a larger area.

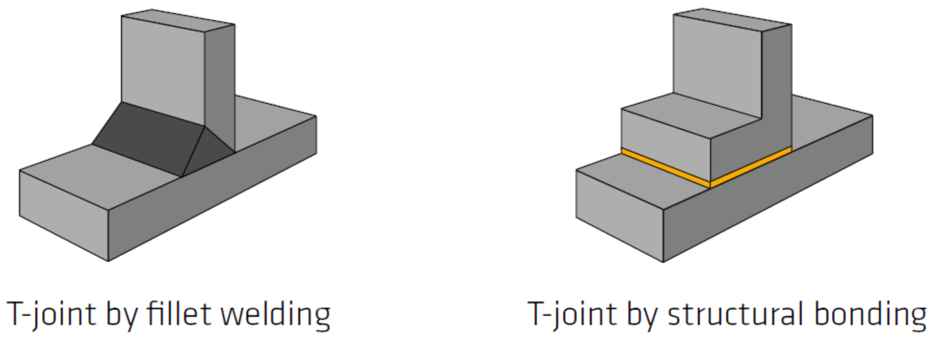


Figure 1 *T-joint design examples for welding and bonding.*

For a successful dimensioning of a bonded joint, mechanical designers and engineers must take into account the four factors illustrated in Figure 2. Not only the adhesive material properties are influential, but also the adherends' characteristics (type, size, mechanics, surfaces, etc.), as well as the geometrical features and the loads that the joint must transfer during its whole operational life. For instance, metallic and plastic adherends may be subjected to stress corrosion and environmental stress cracking respectively, which lead to structural joint failure if neglected or not adequately designed.

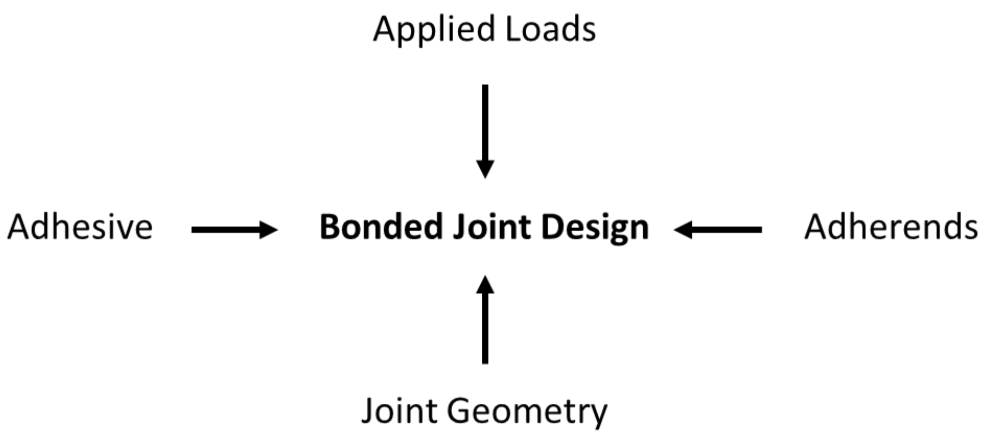


Figure 2 *Factors influencing the design of a bonded joint.*

As the material properties of adhesives and substrates tend to decrease over time due to environmental influence and fatigue, the joint design must consider opportune property knockdown or reduction factors already during the initial development phase. Such a phase is normally followed by design optimization and verification via analytical methods – usually limited to simple joints – or computer simulation knowing the forces acting on the structure. Finally, the joint strength should be validated against actual loads and boundary conditions in real tests.

2.2 TYPES OF STRESSES

Adhesives in bonded joints are generally subjected to one or a combination of different types of stresses. As illustrated in Figure 3, the main stress types are: shear, compression, tension, cleavage (with rigid substrates) and peel (with flexible substrates). Torsion and bending are here not explicitly treated, because the resulting stresses produce similar effects as a combination of the abovementioned stress types.

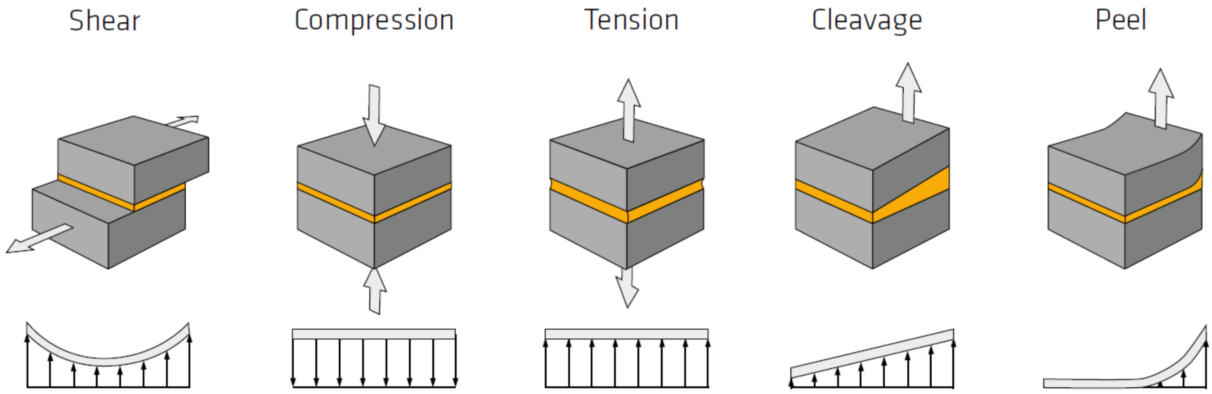


Figure 3 *Fundamental types of stresses in bonded joints.*

Bonded joints are commonly designed to work under shear loading, because adhesives are largely resistant to shear forces and the stresses can be spread over the whole bond area. As shown in Figure 3, shear stress peaks occur at the two ends of the overlap: these extremities carry most of the load and an eventual failure starts from them. The nature of the stress peaks at the overlap ends will be detailed later, but it is worth anticipating that their magnitude depends on the relative stiffness of the adhesive and the adherends. Generally, the more flexible the adhesive is, the more uniform the stress is distributed and the less the stress peaks are pronounced.
Compression and tension loads, applied by stiff substrates, create an even stress distribution in the adhesive layer, which is a favorable design feature. Compression loads are preferred since the adhesives show typically higher strength when compressed, while tensile loads may lead to peeling or cleavage if the adherends deflect or the applied load is offset to any degree. Note that, in the latter case, the stress is no longer evenly distributed: this situation would be similar to a bending and should be prevented.
Peeling and cleavage concentrate high stresses on a single boundary line of the joint. This situation can lead to premature failure and has to be avoided, especially when using rigid adhesives. Joints subjected to peel or cleavage stresses – as well as to bending – should be redesigned for bonding applications.

2.3 BASIC DESIGN PRINCIPLES AND BEST PRACTICES

The basic principles for designing bonded joints can be summarized by the following rules:

- Avoid peel and cleavage stresses; prefer compression and shear stresses.
- Increase the bond area as much as possible within the allowable geometrical and weight constraints.
- Design the joint in such a way that the stresses are as much evenly distributed as possible.

The last point enables a larger percentage of the bond area to contribute to the overall joint strength, reducing stress concentrations.

Converting peel or cleavage into other types of stresses may appear complicated, but actually several reference patterns can be followed. Figure 4 (A to I) illustrates a few examples of best design practices for bonded joints. More examples and joint design methods are given in the reference handbooks [1-3].

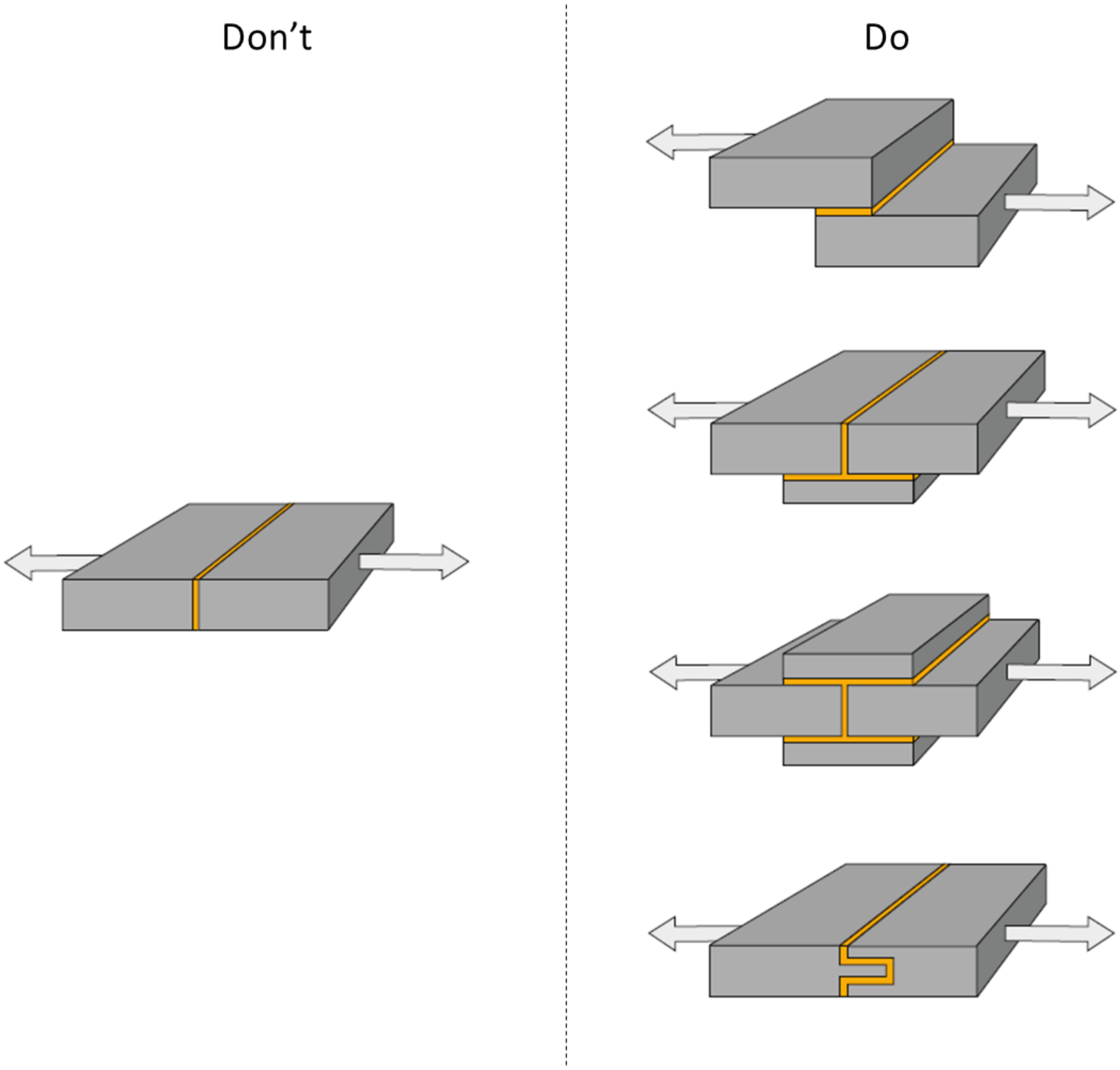


Figure 4 (A) *Best practices for bonded joint design.*

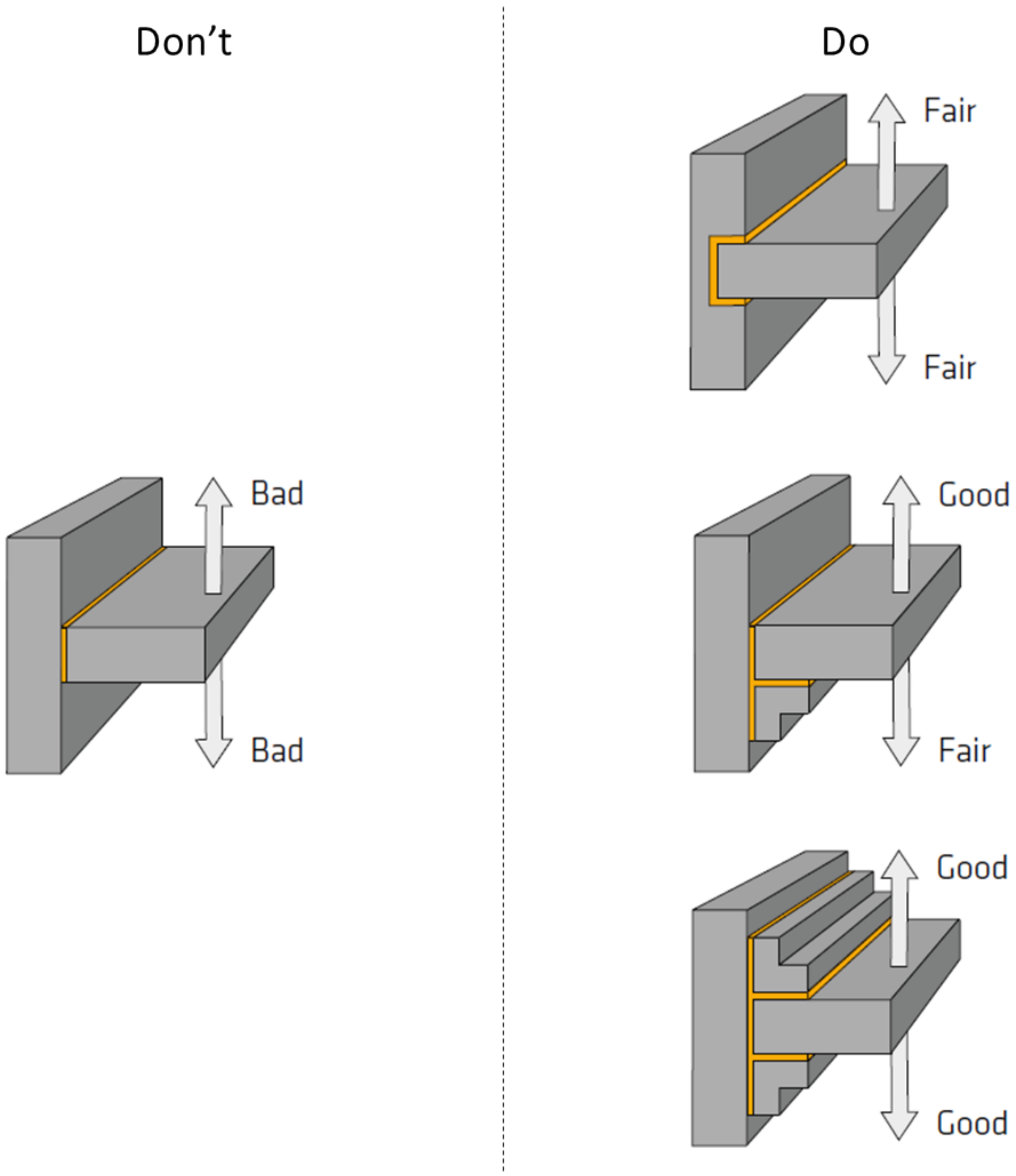


Figure 4 (B) *Best practices for bonded joint design*.

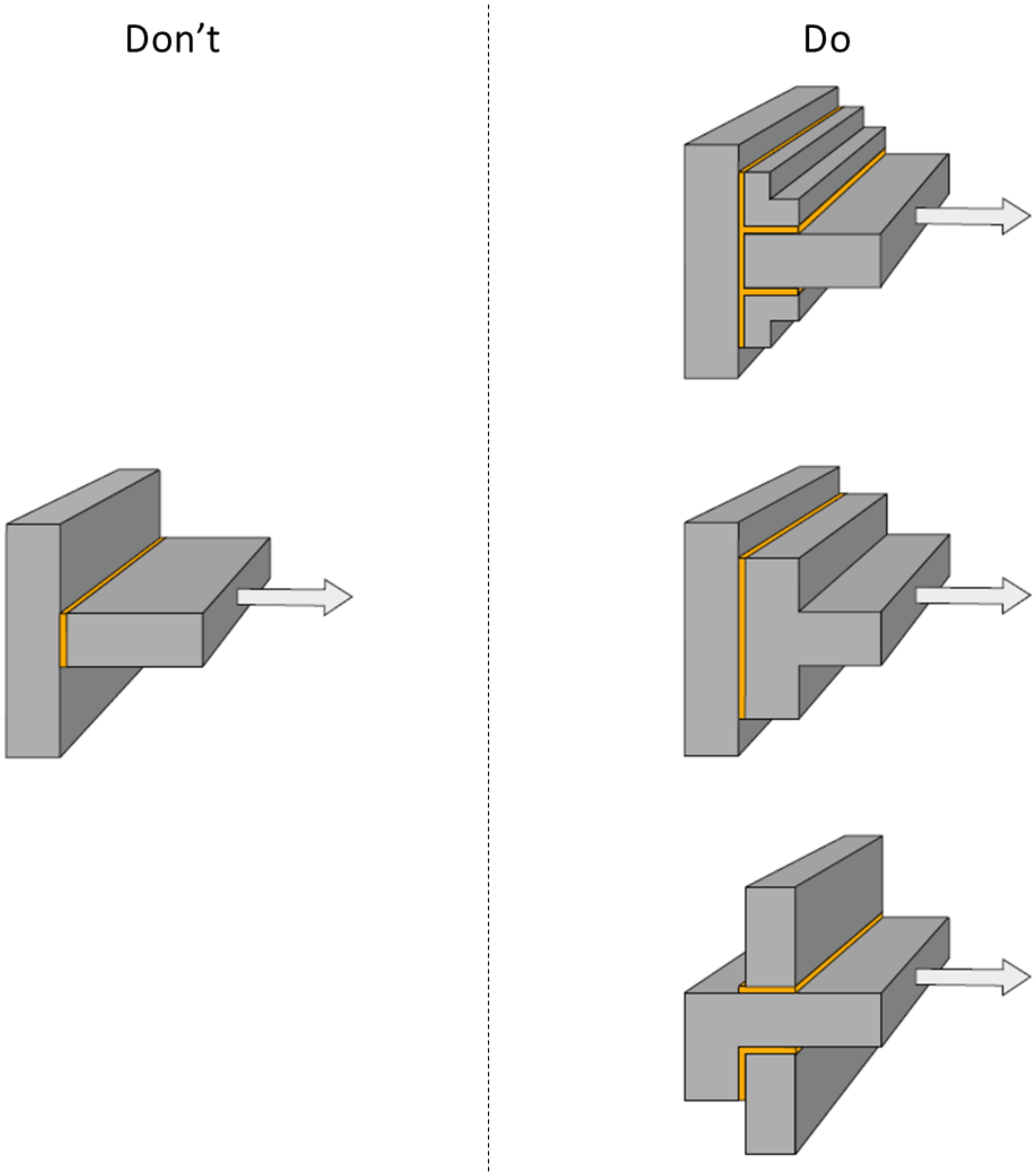


Figure 4 (C) *Best practices for bonded joint design.*

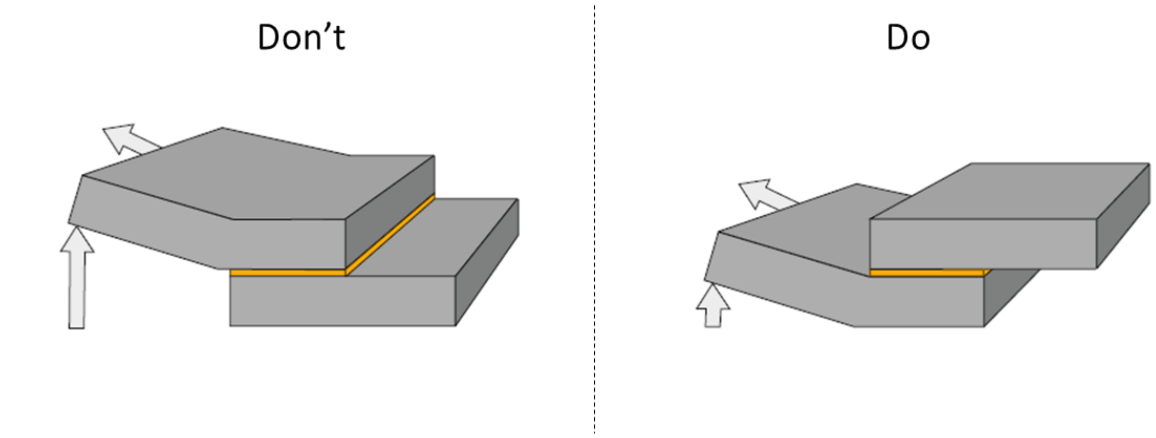


Figure 4 (D) *Best practices for bonded joint design.*

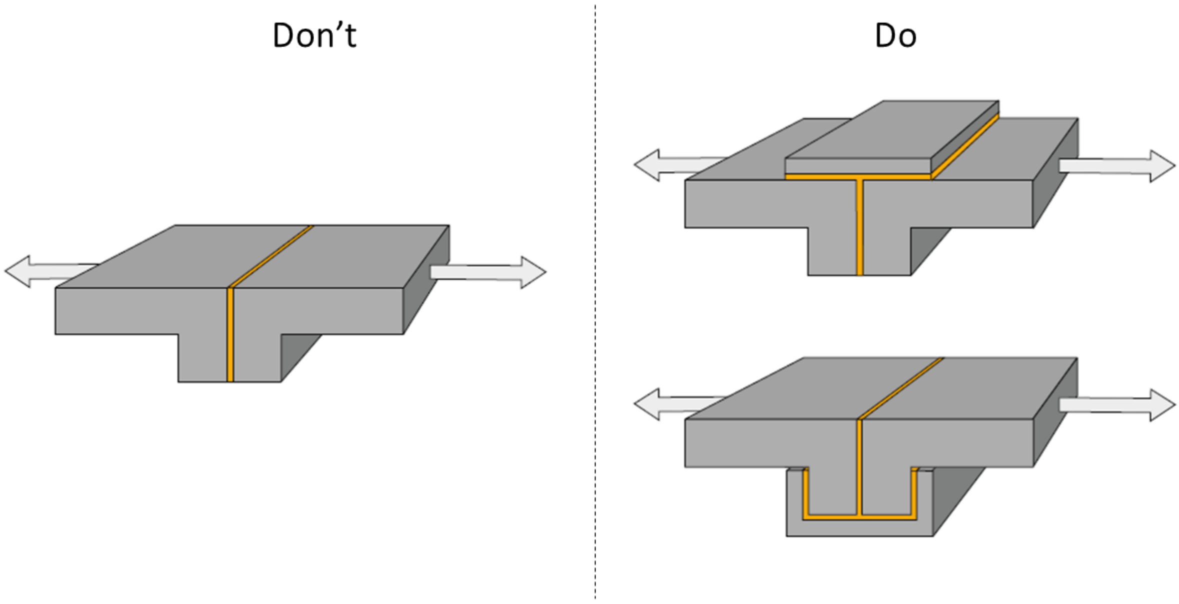


Figure 4 (E) *Best practices for bonded joint design.*

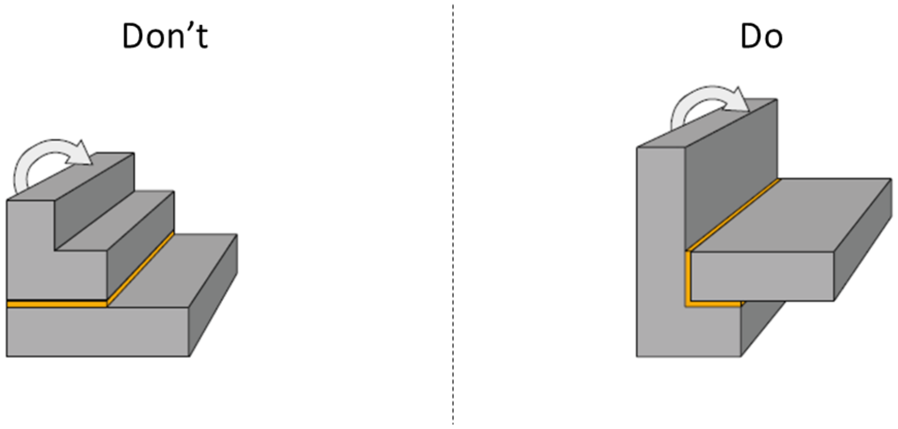


Figure 4 (F) *Best practices for bonded joint design.*

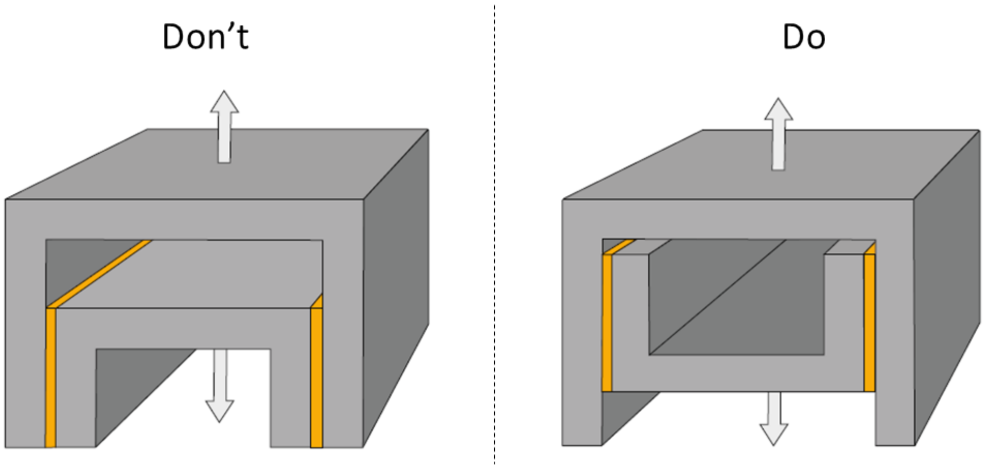


Figure 4 (G) *Best practices for bonded joint design.*

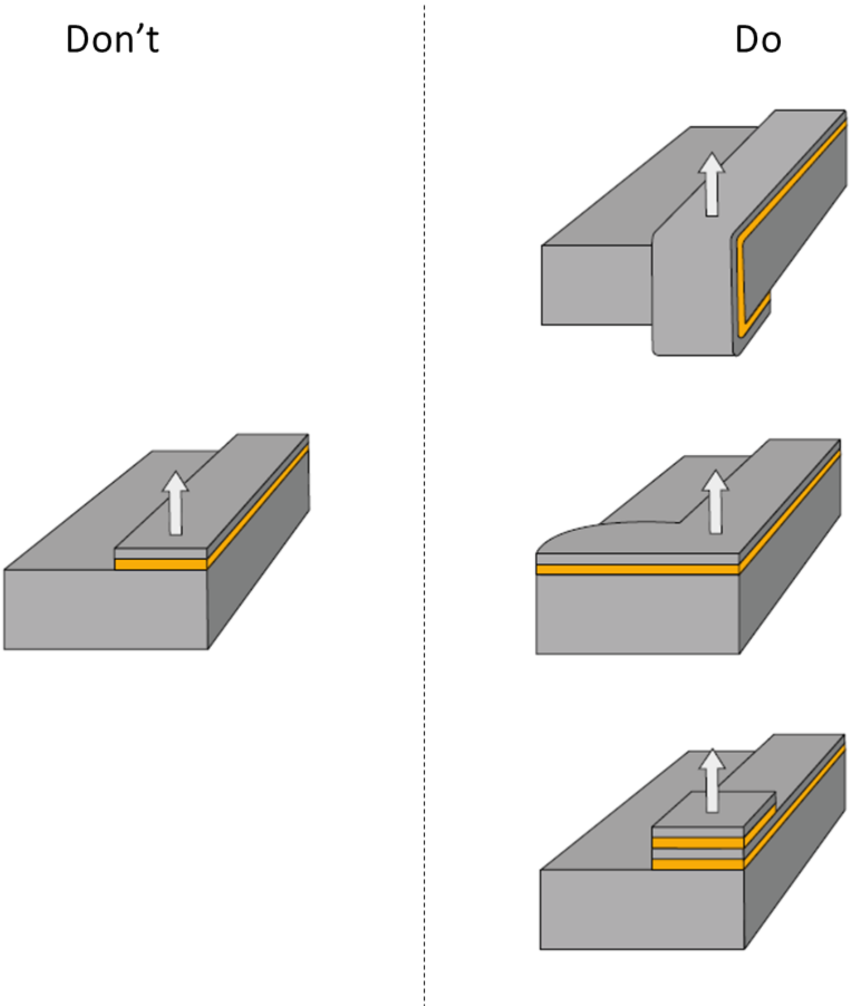


Figure 4 (H) *Best practices for bonded joint design.*

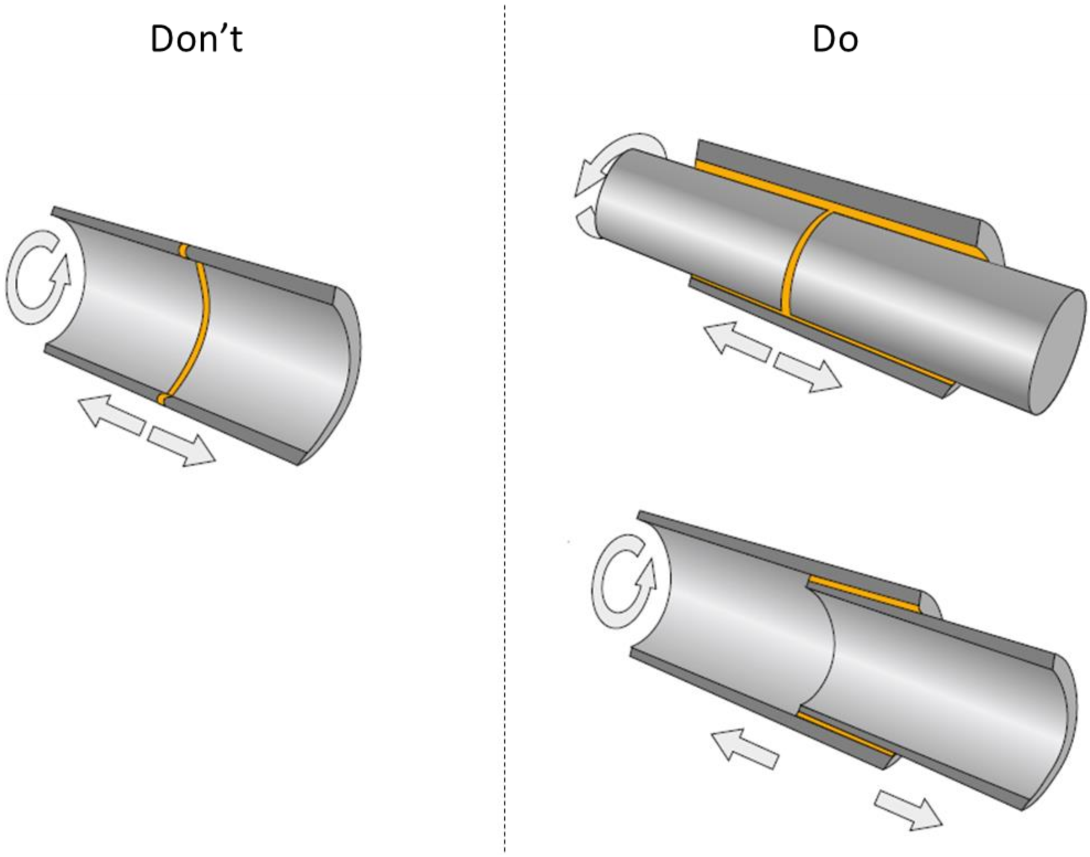


Figure 4 (I) *Best practices for bonded joint design.*

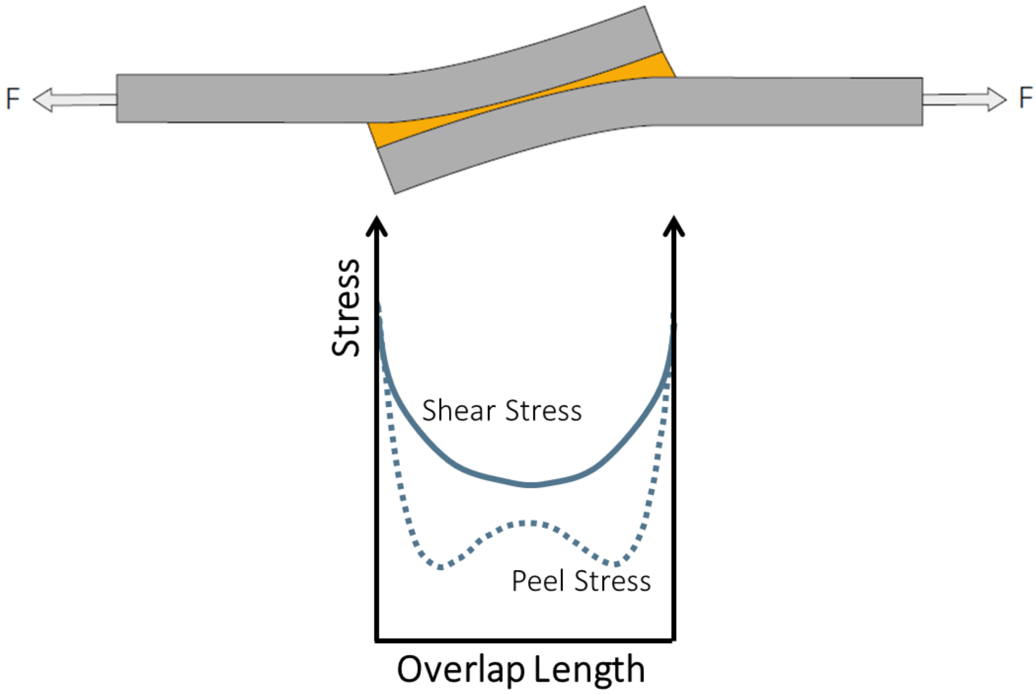


Figure 5 *Bending and stress peaks in single lap joints.*

A single lap joint represents a basic and practical joint design. However, this joint tends to bend under load when bonding thin or not stiff enough substrates, introducing peel/cleavage stresses (Figure 5). Consequently, the shear stress distribution shows peaks at the extremities, as mentioned above. Those stress peaks can be reduced with a tapered lap joint or by creating adhesive bridges as in Figure 6. To make the stress distribution more uniform a scarf or a stepped lap joint can be used. To increase the bond area, a single or double strap joint can be considered. Of course, all those alternative designs will increase the complexity of the joint and may require substrate machining, which is not always feasible or economical.

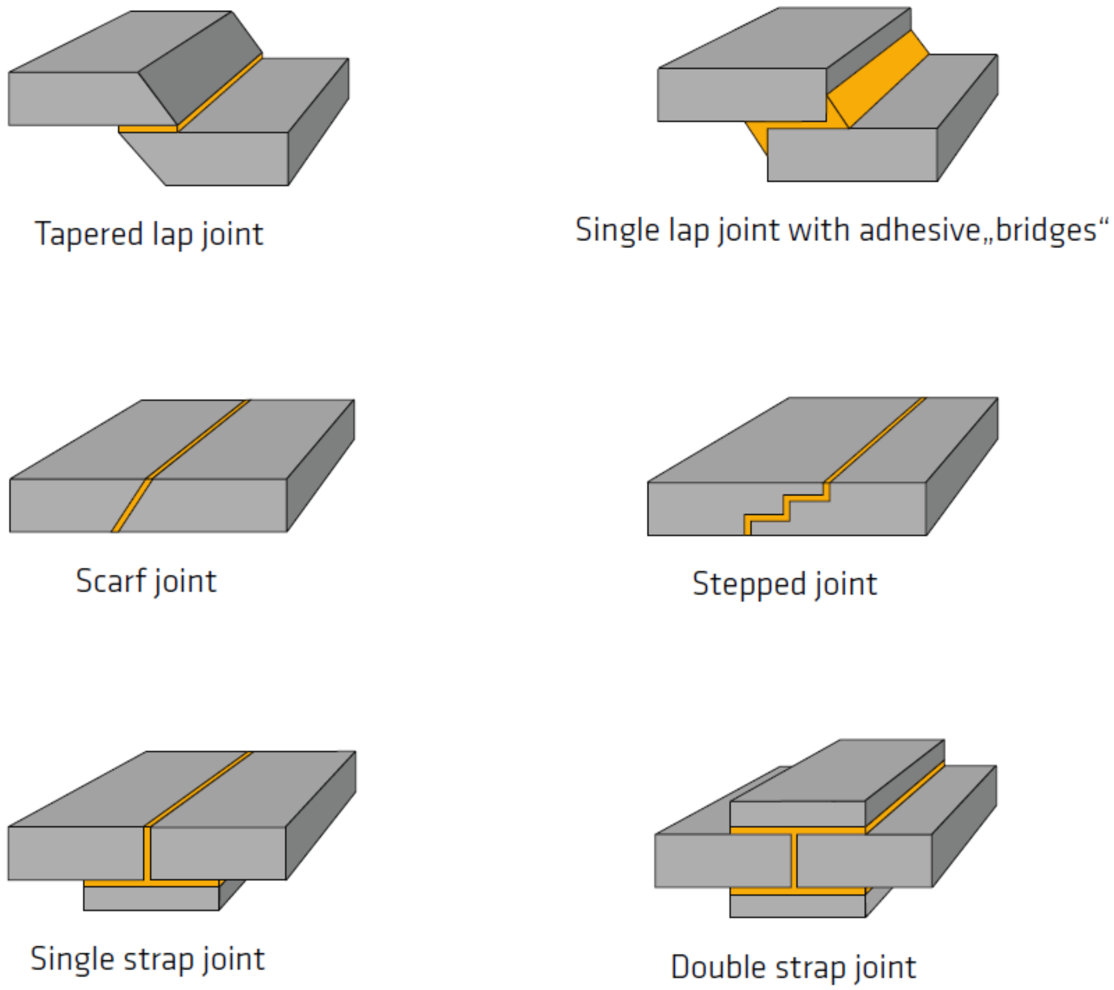


Figure 6 *Improved configurations for simple lap joints.*

2.3.1 DESIGN DEVELOPMENT AND OPTIMIZATION BY COMPUTER SIMULATIONS

While Figures 4 and 6 illustrate best practices and exemplary applications of basic design principles, industrial designers and engineers make nowadays regular use of computer simulations to develop and optimize complex joint geometry. For this purpose, a stress analysis is typically carried out using a Finite Element Method (FEM) software [3-5], in order to identify the critical areas where stresses are concentrated. Geometric features and dimensions of the joint are thus virtually modified and examined in an iterative manner, with the objective of minimizing dangerous stress peaks and ensuring joint integrity by optimal design of the whole parts.

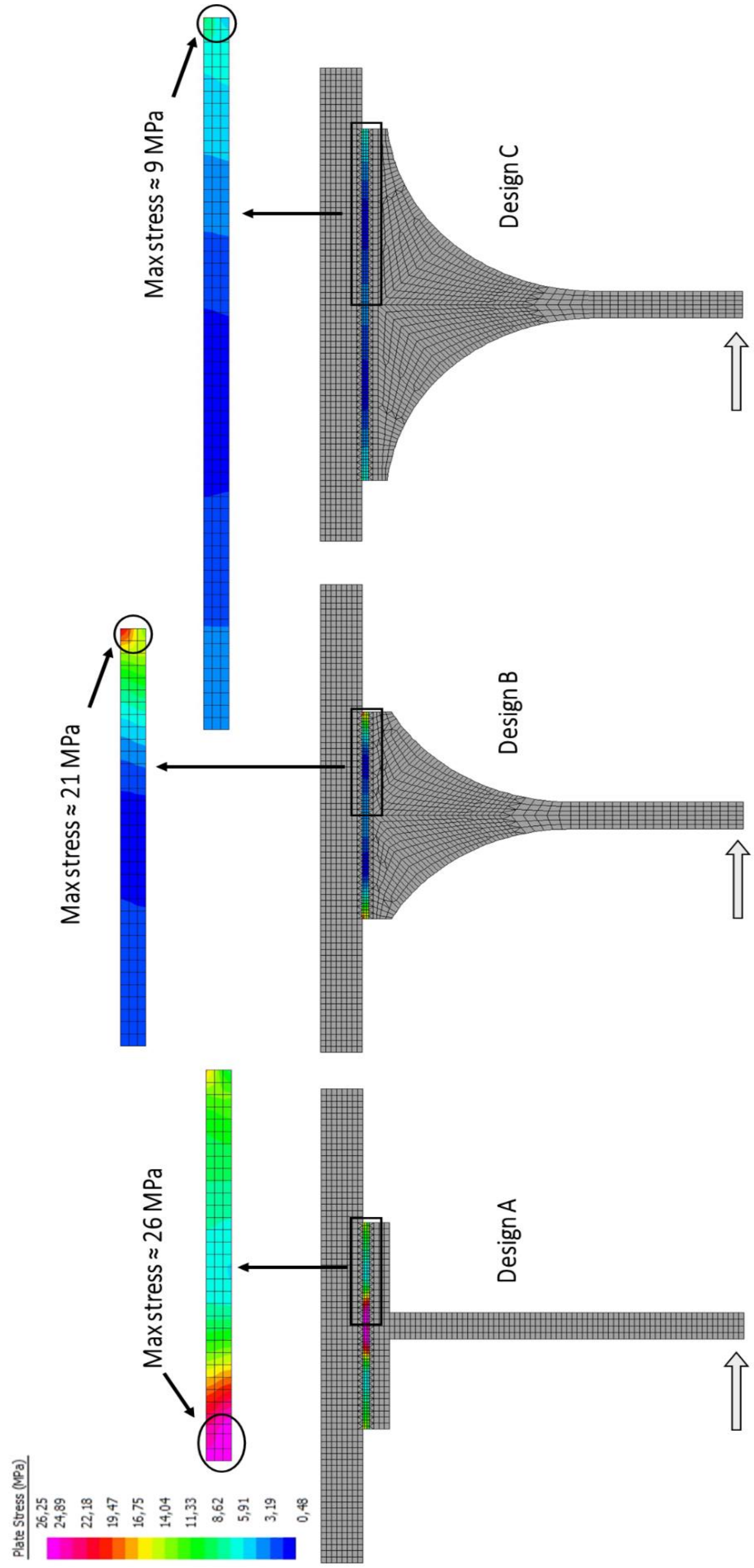


Figure 7 *Stress analysis for different configurations of a simplified fin-to-hull bonding. For each joint design, the obtained symmetrical stress distribution from FEM simulation is zoomed for half bondline.*

Figures 7 and 8 show two examples, in which computer simulations are employed to optimize the part design for bonding applications. Figure 7 illustrates the simplified case of a composite fin, represented by a vertical appendix, which is bonded beneath the ship hull. At its tip, the fin is subjected to a side force that produces bending and shear in the bondline. For the joint design of the left picture (Design A), high levels of stress are generated: the peak reaches a value of approximately 26 MPa and is localized in the central zone of the bondline. The position of such stress peak hints that the fin is not stiff enough to spread the stresses – especially those ascribable to the bending – over the whole bonded area. The middle picture in Figure 7 (Design B) shows how the stress distribution can be largely improved by just modifying the fin geometry, increasing its stiffness: stress peaks in the adhesive decrease to 21 MPa and are shifted to the extremities of the bondline. Finally, if the bondline is extended as in the right picture of Figure 7 (Design C), the stresses are even more uniformly distributed and peaks are largely reduced to only 9 MPa.

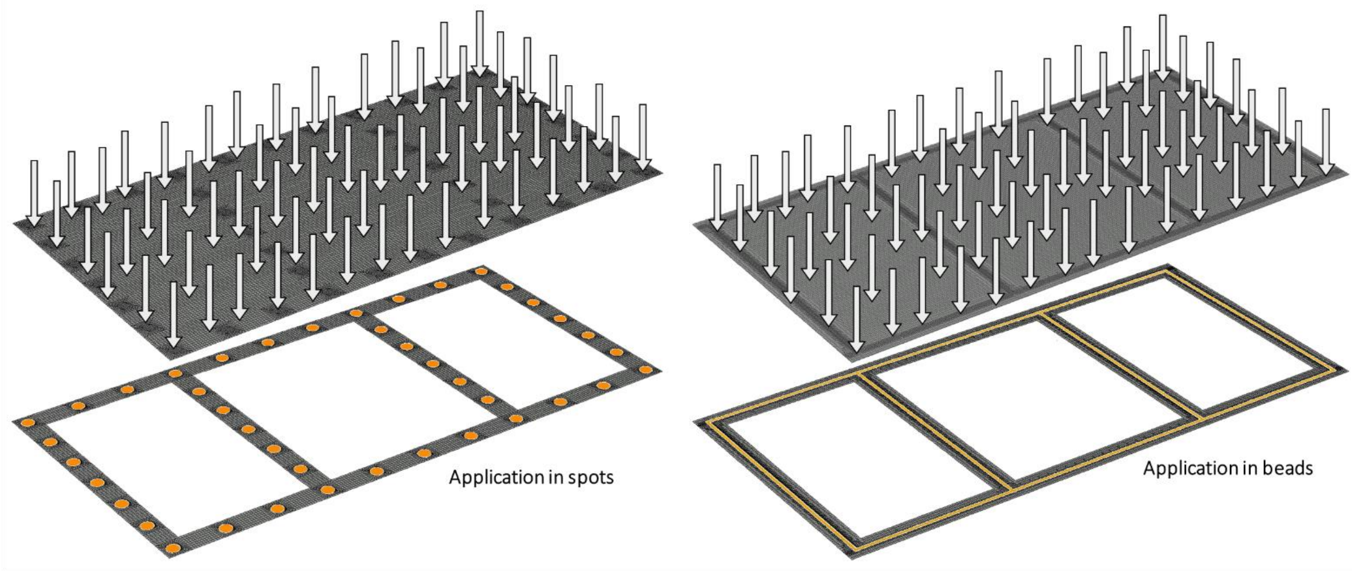


Figure 8 (A) *Stress analysis of a stiffening frame bonding with spot application (left picture) and bead application (right picture): forces and joint configurations.*

Figure 8 depicts the case of a stiffened metallic platform, in which spotwelds are replaced with an adhesive bond. In the left picture of Figure 8 (A), the adhesive is pointwise applied to bond the stiffening frame, as if the spotwelds were literally replaced by adhesive spots. In the right picture, the adhesive is applied by continuous beads, keeping overall the same bonding area of the adhesive spots of the left picture. Figure 8 (B) shows how these different application methods affect the deformation and the stress distribution in the platform. In the case of spot application of the adhesive, similarly to spotwelds, high stresses are localized around the spots reaching values of about 70 MPa. On the contrary, the bead application leads to a more homogeneous stress distribution; moreover, maximum values that are almost halved. In Figure 8 (C), the stress inside the adhesive layer is highlighted: the results confirm that the spot application is not ideal, because it does not exploit the potential the adhesive offers to distribute stress and to decrease the risk of local failures. As noticeable high stresses (ca. 25 MPa) are localized on the outskirts of the adhesive spots, while a mostly uniform stress distribution, with peaks of maximum 7 MPa, is achieved in the case of continuous beads.

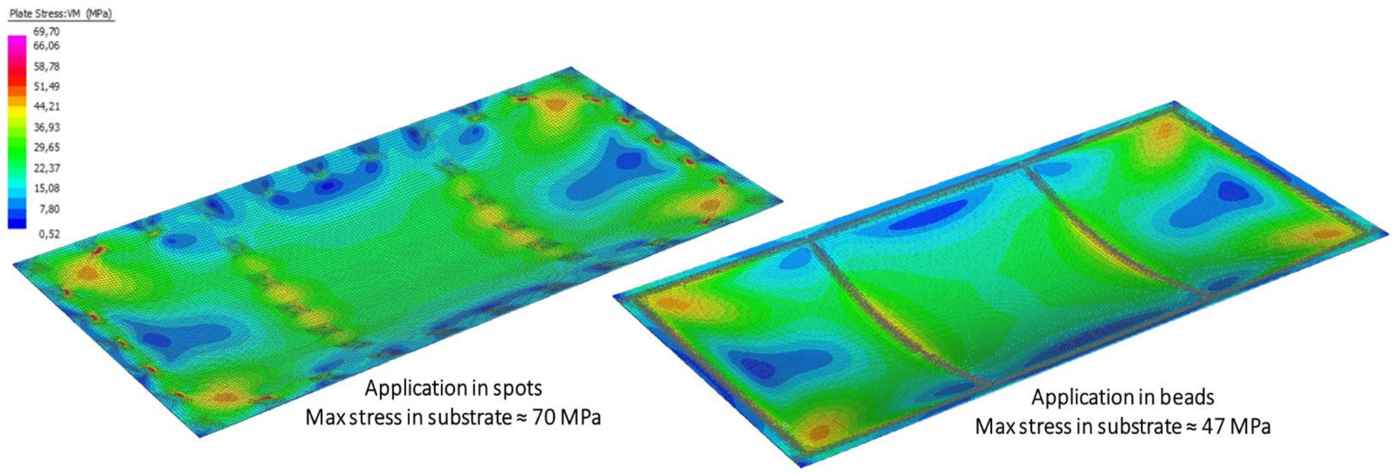


Figure 8 (B) *Stress analysis of a stiffening frame bonding with spot application (left picture) and bead application (right picture): deformation and stress in the substrate plate.*

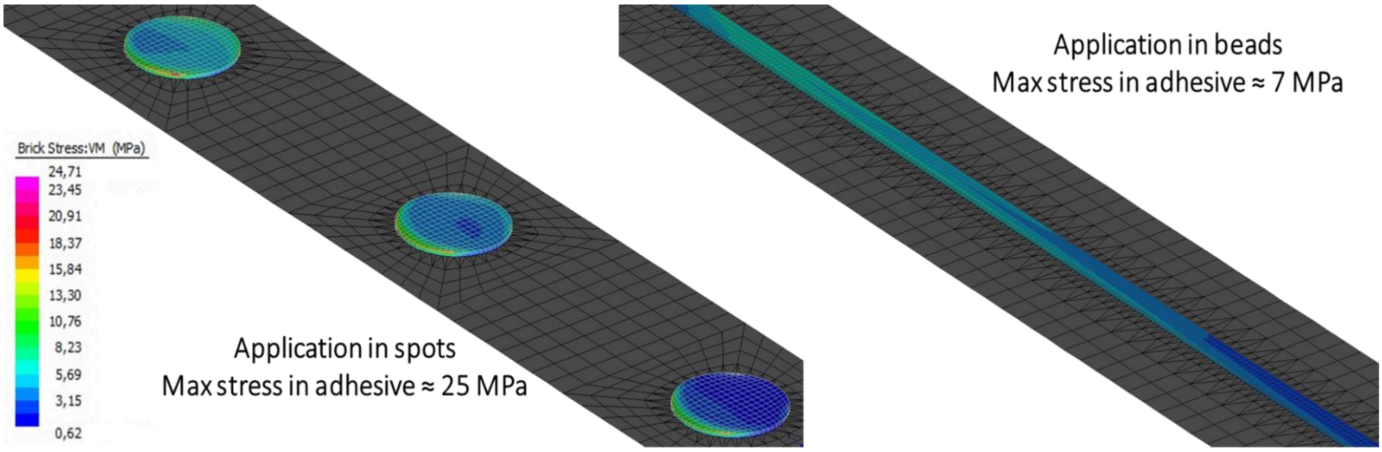


Figure 8 (C) *Stress analysis of a stiffening frame bonding with spot application (left picture) and bead application (right picture): stress distribution in the adhesive.*

The cases of Figures 7 and 8 are here treated as illustrative examples only; the present document does not aim to offer comprehensive guidelines for modeling and investigation of structural adhesives via FEM. Nevertheless, below is a list of practical information for generic simulation of adhesive bonds:

- Brick (i.e., volume) elements are normally suited for modeling bondlines of rigid adhesive layers, because they allow the representation of stress and deformation with great accuracy within their section and can catch local stress peaks well
- As a compromise among model complexity, computational time and accuracy, it is usually recommended to employ at least two quadratic volume elements or three linear volume elements along the joint thickness. On the one side, more the used elements are, more accurate the simulation of the mechanical behavior is. On the other side, the thinner the adhesive layer is, the higher the model complexity and computational time become if big parts must be simulated.
- The ideal shape for a brick element is a cube. If not cubic, it is important to check that the aspect ratio of the elements (ratio of the maximum to the minimum edge length) is less than 3. However, depending on the software, different reliability criteria can apply.

- To minimize computational time and model complexity for systems including big components (namely, when a large number of finite elements must be created), a suggested approach is to develop preliminary FE models simulating the joints by simpler elements (e.g., springs, plate, etc.), in order to easily identify the locations of the maximum stress. Once those locations are identified, partial FE sub-models for maximum stress areas can be created by modeling the joints with greater accuracy thanks to brick elements.
- The specific elements used in FEM – spring, plate, brick elements, etc. – affect the numerical value of the material parameters (like elastic and shear modulus) to input into the model. Note also that material parameters and laws are often bounded by given deformation limits.
- In order to check the joint integrity, their contribution to stiffening parts and the overall deflections of the simulated system, all loads and load combinations must be implemented as unfactored in the FE model: in technical words, the loads must be defined at the Serviceability Limit State (SLS).
- The FE analysis must be run through a geometrical non-linear solver to account for second-order effects, which may occur in the deformation of the bonded components.

2.4 SCALING RULES FOR LAP JOINTS

The single lap joint geometry (Figure 9) is here taken as reference to guide the dimensioning of structurally bonded joints. As previously stated, the bond area shall be as large as possible to increase the capacity of the joint to transfer load – that is for simplicity named the joint "strength". Nevertheless, the bond width and the overlap have different effects, as shown in Figure 10. The total strength increases linearly with the bond width, while the strength increment is not proportional to the overlap length. In particular, the longer the overlap is, the smaller the gain in strength is. This effect is more visible if the adhesive is more rigid. On the contrary, the relation between overlap and joint strength tends to be almost linear with flexible adhesives. This behavior is explained by the fact that the overlap extremities are characterized by stress peaks especially in rigid or thin-layered adhesives (Figure 6). Increasing the overlap length does not heighten these load-carrying peaks, but rather extends the middle part of the stress distribution that contributes less to the load transfer.

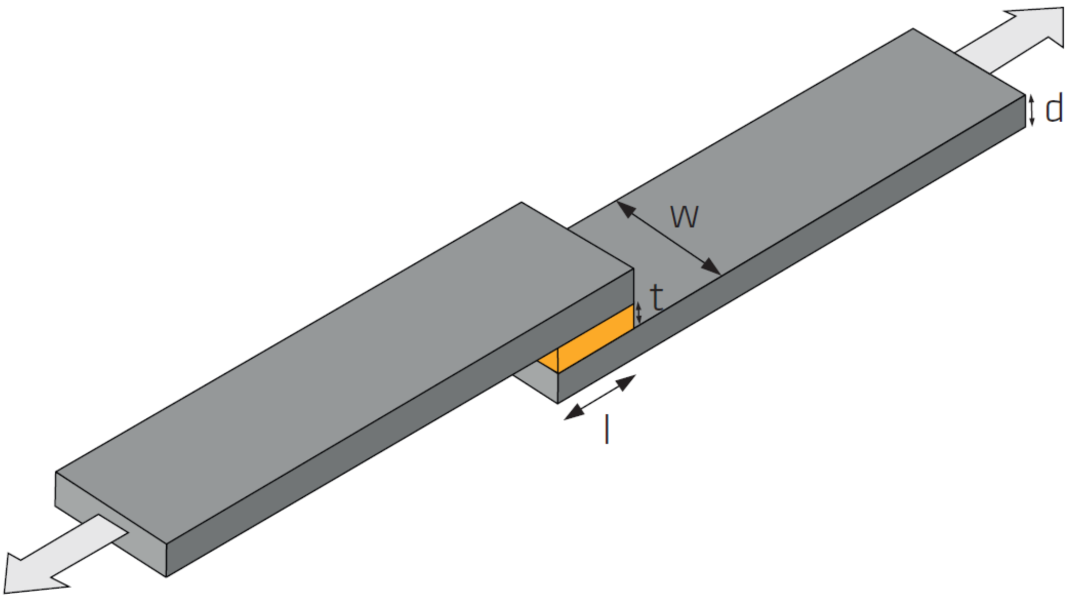


Figure 9 *Single lap joint geometry.*

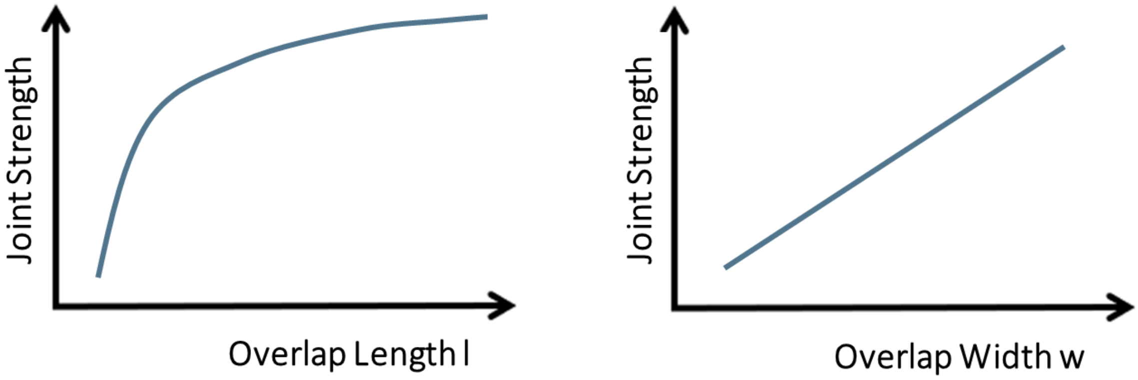


Figure 10 *Effects of overlap length and width on joint strength in single lap shear.*

Figure 11 presents an important consequence of the peculiar stress distribution in rigid adhesive bonding: although the illustrated joint designs have equal bond area, the strength of design B (larger width) is more than 10 MPa higher than the one of A (larger length). This difference in strength tends to reduce the more flexible the used adhesive is.

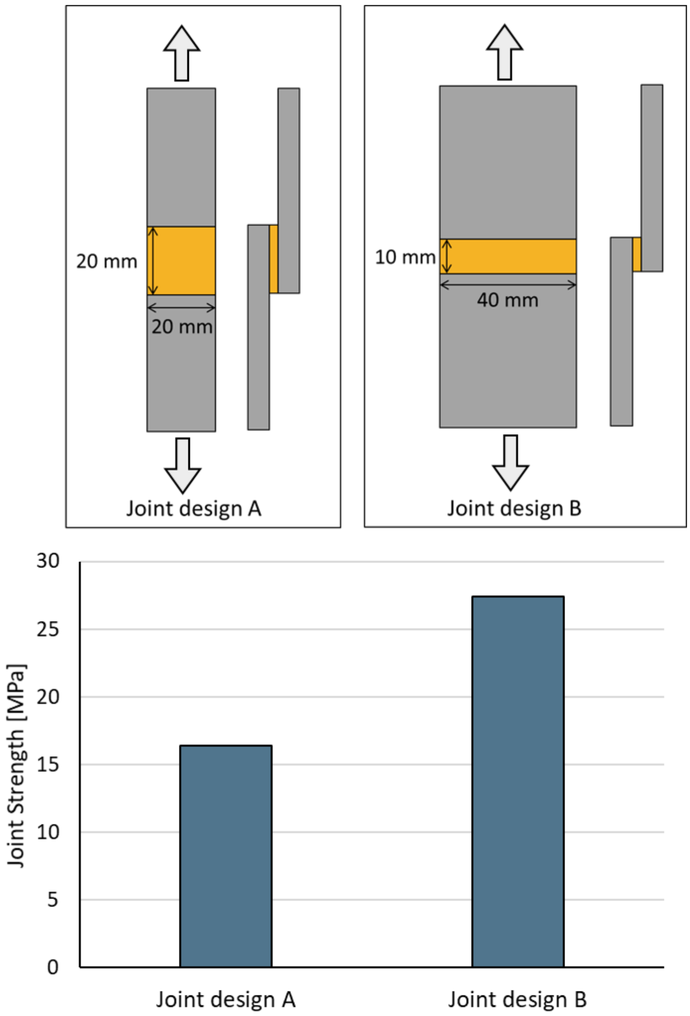


Figure 11 *Strength comparison of joints bonded with the same rigid SikaPower® adhesive: the two joints have equal areas but different overlap length and width, resulting in different final strength.*

The influence of the adhesive layer thickness on the joint strength is shown by Figure 12. The highest strength is normally reached at a thickness of about 0.2-0.3 mm. Many structural adhesives contain glass beads, acting as spacers to ensure this optimal thickness is matched. For larger thicknesses, the joint strength decreases until a plateau is typically reached. This is often the case when using flexible adhesives, with which the strength shows virtually no variations at thicknesses from 3-5 mm to a few centimeters.

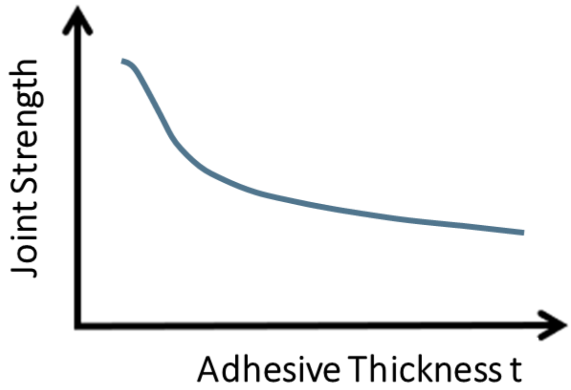
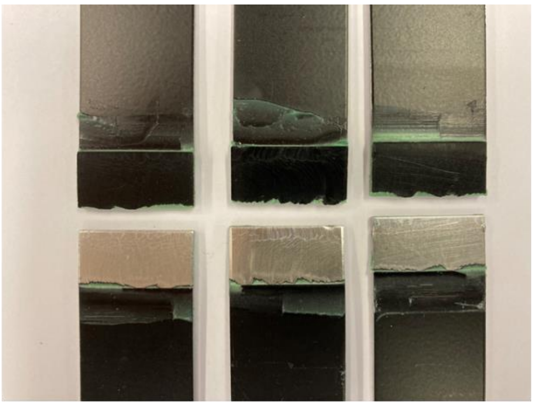


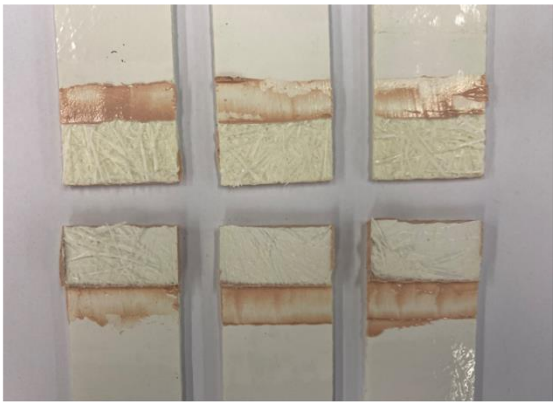
Figure 12 *Effects of adhesive thickness on joint strength.*

2.4.1 INFLUENCE OF THE ADHERENDS

The design principles and rules are exposed so far with focus on adhesive size and features like rigidity and flexibility. However, it is worth reminding that the joint strength depends also on the adherends, among other factors (Figure 1). Specifically, bulk mechanical properties and surface characteristics of the substrates to bond play a fundamental role. The success of a bonding application is ultimately defined by a proper match of adhesive and adherends, with maximum achievable strength that is limited by the one or the others. Figure 13 shows broken lap-shear samples of powder coated metal alloys and glass-fiber reinforced (GFR) plastic laminates: in the first case a coating rupture was obtained, in the second case the failure occurred because of delamination. In both cases, the adhesive material was stronger than the substrates themselves.



Coating rupture in powder coated metals



Delamination in GFR plastics

Figure 13 *Failure patterns in powder coated metals and GFR plastics.*

Generally speaking, the relative stiffness of the adhesive compared to the adherends is a key parameter for joint design. The likelihood of bending as in Figure 5 increases when the rigidity of the adherends decreases. Therefore, more pliable substrates lead to higher peeling and shear stress peaks, which should be accommodated by employing more flexible adhesives that can spread stresses more homogeneously within the bondlines. Similarly, in multimaterial joints, large movements due to different substrates' thermal expansion coefficients should be compensated by creating joints with the use of flexible or semi-rigid adhesives. Since soft joints form compliant structures, they require larger bonding areas to transfer the same loads of stiff joints. The features of these different joint types – rigid, semi-rigid or flexible – can be advantageously exploited depending on the foreseen application and design of the whole structure (Figure 14).

Figure 14 *Exemplary industrial applications of bonded joints: rigid (wind turbine blade and metal chassis bonding), semi-rigid (caravan and bus modular bonding) and flexible (windshield and panel bonding) joints.*

The thickness of the adherends has a similar influence as their inherent rigidity on the joint strength, because thinner substrates are also less stiff. When bonding thin metal sheets, as in lightweight vehicle bodies for example, the joint strength can be expressed as a function of the joint factor [1], namely the ratio of the substrates' thickness *d* to the overlap length *l* (Figure 15). In order to avoid joint strength reduction, a low thickness of the adherends may be compensated by a short overlap. However, in common praxis, it is unusual to work with an overlap length lower than 10 mm.

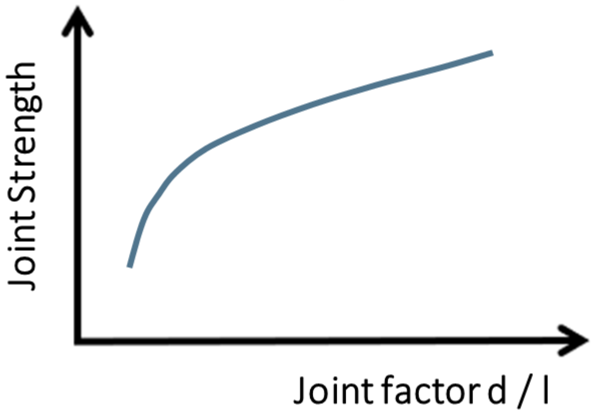


Figure 15 *Joint strength as a function of the joint factor (substrates thickness to overlap length ratio).*

2.5 DIMENSIONING WITH MATERIAL REDUCTION FACTORS

Once a suitable joint geometry has been sketched, its dimensions can be fine-tuned considering the effective capability of the adhesive to transfer loads throughout its operational life. Environmental conditions as well as fatigue and creep tend to reduce the adhesive mechanical properties over time: those phenomena must be taken into account by designers to avoid premature joint failure. For the same reason, the actual adhesive thickness (see Figure 12) and service temperature (Figure 16) must be considered for design purposes, because they influence the final material strength. While temperature effects are often negligible for interior applications, they are particularly important, e.g., when bonding vehicle components that travel across a variety of climatic conditions. Depending on the area of use, service temperatures may range from -20 °C to 80 °C. Within this interval, the adhesive strength and elasticity may show significant variations compared to datasheet values measured at room temperature. Joint dimensioning should be based on material data representing the critical scenarios that may occur in service life, like the extremes of the service temperature range, namely the minimum and maximum temperatures at which the assembly is designed to regularly work for a prolonged time.

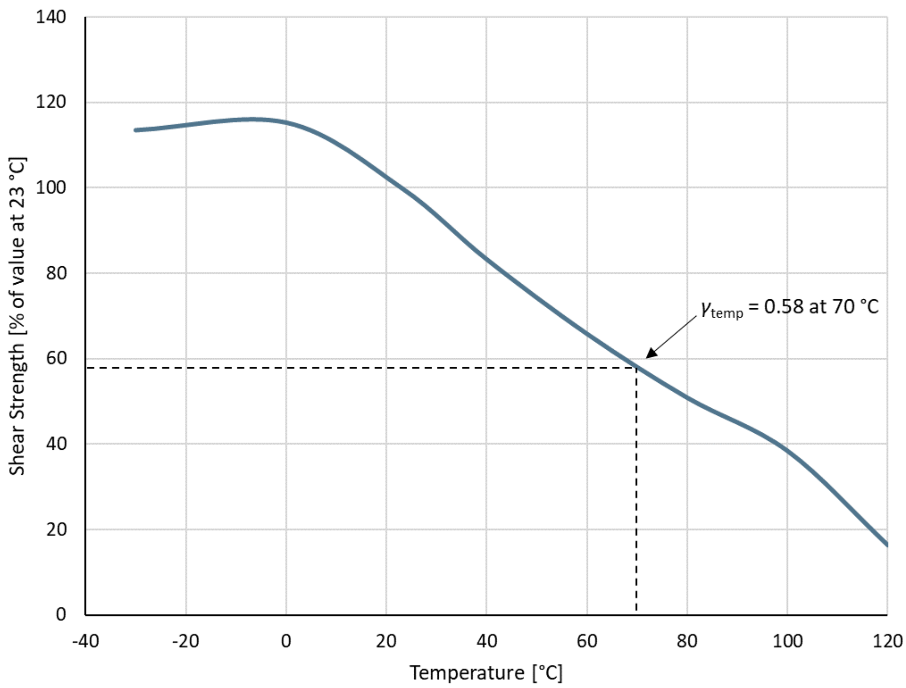


Figure 16 *Exemplary temperature dependency of the adhesive strength.*

A possible simple approach to evaluate the allowable design strength for given boundary conditions involves the introduction of reduction factors for each influencing parameter according to the following formula:

$$\tau_a = \tau_c \cdot \gamma_{temp} \cdot \gamma_{thick} \cdot \gamma_{aging} \cdot \gamma_{load} \cdots / S_d \quad (1)$$

where τ_a is the max allowable strength, τ_c is the reference or characteristic strength of the unaged adhesive associated to the substrates and pretreatments that are used, the parameters γ's are the strength reduction factors (for temperature, thickness, environmental aging, lifetime loads, etc.) and finally S_d is the design safety factor.

The reduction factors can be easily determined by specific tests, such as lap-shear tests, comparing the results of e.g. aged samples versus unaged samples (Figure 17). The resulting strength decrease in percentage represents the specific reduction factor. Reference sets of reduction factors for selected Sika products are available in technical documents like Additional Product Information (API) or material cards.

In many applications, checking the joint integrity could require a separate calculation of the max allowable strength for different boundary conditions and load case scenarios. For example, as fatigue and creep loads do not occur together, they are treated independently, leading to two different values of τ_a. Note that, for any load case scenario, the calculation of τ_a must not include each and every reduction factor as in Equation (1), but only those factors that are relevant to the case, according to the specific application conditions and expected environmental influence in service. All other factors that are irrelevant or inapplicable are simply set to 1.

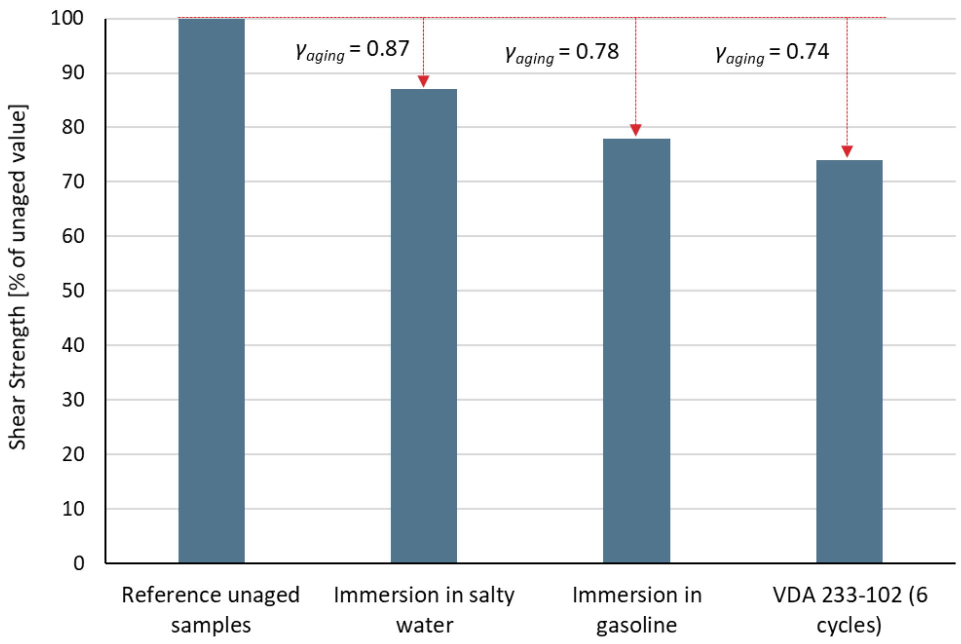


Figure 17 *Exemplary reduction factors for environmental aging of a SikaPower® adhesive.*

IMPORTANT NOTE

Reduction factors shall not be confused with safety factors. The reduction factors account for the factual change of material strength because of long-term aging phenomena and of different temperature or thickness (compared to reference or datasheet strength). On the contrary, the safety factor S_d is a pure risk parameter considering application and material uncertainties. It must always be included in the calculation of the allowable design strength and shall be set according to the specific application cases and eventual normative instructions. In absence of references, the safety factor is commonly chosen between 1.5 and 2.5, depending on the risk assessment.

Figure 18 *Railway vehicle door bonding with a SikaPower® adhesive.*

A practical case of allowable strength calculation is hereafter provided, referring to the assembly bonding of train doors with a two-component SikaPower® adhesive (Figure 18). The characteristic shear strength of the adhesive – measured on the application substrates – is 28 MPa. This represents the reference or starting strength value of the unaged adhesive with a thickness of 0.3 mm at room temperature (23 °C). For the considered application, the railway vehicle designers take the following factors into consideration:

- *Temperature* – The maximum service temperature, for which the train doors are supposed to operate according to rail standards, is 70 °C. According to the graph of Figure 16, which is specific for the selected adhesive, the strength reduces by a factor 0.58 at 70 °C. This corresponds to approximately 16 MPa
- *Thickness* – The applied layer thickness (0.3 mm) is the same as the reference thickness at which the characteristic strength is measured. Therefore, the corresponding reduction factor is 1 (namely, no strength reduction).
- *Environmental aging* – Manufacturers of train components contemplate a possible water infiltration in untightened door assemblies. Specific aging tests, conducted by full immersion of bonded samples in water up to three months, showed the joint strength is marginally affected by aging, since 94 % of the starting strength is retained (reduction factor is 0.94). Other kinds of environmental or chemical aging are considered even less relevant for the application and the selected adhesive. It is worth pointing out that in many cases the environmental effects can be neglected because structural joints are protected by sealants or anti-corrosion paints/treatments, as well as narrow joint gaps and long diffusion distances contribute to minimize the influence of environmental/chemical aging.
- *Lifetime load* – Each type of load has a specific occurrence: for instance, a crash is a one-time event; loads caused by emergency break activations could instead occur hundreds of times during the service life of a train; finally small vibration loads are likely to occur more often. As above mentioned, each load case is reviewed separately. In this example the focus is on fatigue due to vibrations. Figure 19 displays the adhesive behavior under fatigue, namely, the average strength at failure as a function on the number of applied load cycles (S-N curve). Although a direct relationship between vehicle service life in years and tested load cycles cannot be formulated, adhesive users may estimate the expected lifetime load cycles by industry standards, international norms or past experiences. For the application case of Figure 19, manufacturers conservatively design the joints to withstand two million load cycles, corresponding to about 10.9 MPa on the curve of Figure 19 and, thus, to a reduction factor of about 0.39.

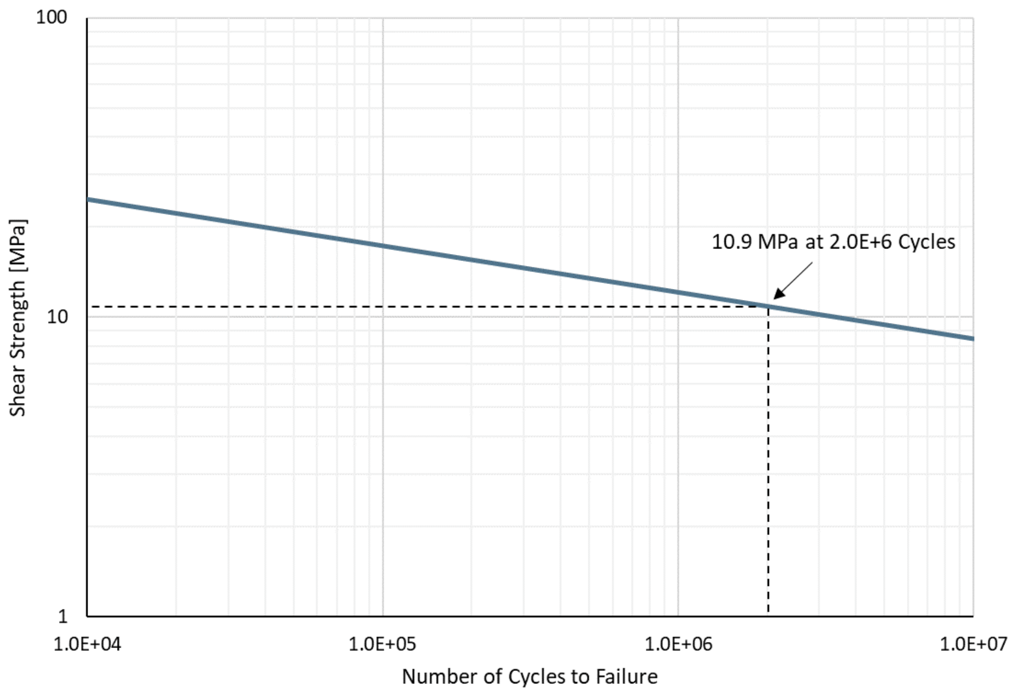


Figure 19 *Exemplary fatigue curve for SikaPower® epoxy adhesive.*

Collecting all relevant reduction factors, the max allowable strength is easily calculated as follows:

$$\tau_a = \tau_c \cdot \gamma_{temp} \cdot \gamma_{aging} \cdot \gamma_{load} / S_d = 28 \text{ MPa} \cdot 0.58 \cdot 0.94 \cdot 0.39 \;/\; 2 = 3 \text{ MPa} \quad (2)$$

where the safety factor is set equal to 2 for the considered joint.

2.6 STRESS CALCULATION AND FAILURE CRITERIA

The max allowable strength from Equation (1) is to be compared to the expected stresses in the bondline depending on joint geometry and applied forces. Either analytical or numerical methods can be used to determine stresses during the design phase. Usually, analytical methods are applicable only for simple geometries and load conditions. As an example for single lap joint (Figure 6), the easiest approach, which is valid under the assumption of adherends much stiffer than the adhesive, considers a uniform shear stress τ that is equal to:

$$\tau = \tau_{mean} = \frac{F}{A} = \frac{F}{l \cdot w} \quad (3)$$

where *F* is the applied force and *A* the bonding area ($A = l \cdot w$). Obviously, the model of Equation (3) neglects the aforementioned stress peaks at overlap ends; however, it could serve for a preliminary rough estimation of the stress level in the adhesive layer.

For an overview of the various analytical methods – proposed by Volkersen, Goland and Reissner, Bigwood and Crocombe, Hart-Smith, etc. – the Handbook of Adhesion Technology [3] can be consulted. Here it is worth presenting Volkersen's equation, which enables the calculation of the stress peaks (although his model disregards peeling stress). According to Volkersen, the maximum shear stress τ_{max} at the overlap ends can be evaluated as follows:

$$\tau_{max} = \tau_{mean} \sqrt{\frac{D}{W}} \cdot \left(\frac{W - 1 + \cosh \sqrt{DW}}{\sinh \sqrt{DW}} \right) \quad (4)$$

in which *D* and *W* are so defined:

$$D = \frac{Gl^2}{E_2 d_2 t} \qquad W = \frac{E_1 d_1 + E_2 d_2}{E_1 d_1} \tag{5}$$

where G is the shear modulus of the adhesive, while E_1, E_2 and d_1, d_2 are the elastic moduli and thicknesses of two bonded substrates 1, 2 respectively (with $E_1d_1 > E_2d_2$). In the case the two substrates are identical, Equation (4) simplifies to:

$$\tau_{max} = \tau_{mean}\sqrt{D/2} \cdot \coth\sqrt{D/2} \tag{6}$$

Equations (4) and (6) show how the stress depends not only on the adhesive material properties, but also on the adherends' stiffness (modulus and thickness).

For complex joint geometries or load cases, a numerical approach such as FEM to calculate stresses is often the only way to go. As anticipated in Section 2.3.1, the description of computer simulation techniques based on FEM is beyond the scope of this introductory guide. Nevertheless, it is important to remark that software for stress calculations requires the following inputs: (a) material models and corresponding parameters, (b) boundary conditions in the form of e.g. external forces or imposed displacements and constraints, (c) the creation of an adequate mesh, which is enough fine to represent stress gradients in the bonded joints.

A simple linear elastic model is generally employed to describe the mechanical behavior of structural adhesives for small deformations (which usually correspond to the target application range). Since the adhesive behavior can be considered isotropic, the elastic modulus E and Poisson's ratio v are sufficient as input parameters for computer simulations. In the case of larger deformations or more sophisticated material models, additional parameters or complete stress-strain curves would be needed: they can be determined by suitable characterization tests. As far as the inputs for external forces/strains are concerned, these can be evaluated by knowing the applied loads on the joint or by measuring them via load cells or even strain gauges [6].

Once the stresses in the bondline have been estimated by an analytical formula or calculated through a FEM simulation, the joint design can be finally verified by comparing the highest stresses to the max allowable strength introduced in Section 2.5. Various failure criteria could be used for this verification [3]. The simplest and often most conservative failure criterion is expressed by the following formulas:

$$\sigma_{max} \leq \sigma_a \qquad \tau_{max} \leq \tau_a \qquad \sqrt{(\sigma_{max}/\sigma_a)^2 + (\tau_{max}/\tau_a)^2} \leq 1 \tag{7}$$

In Equation (7), the first formula checks that the calculated max tensile or peel stress σ_{max} is not higher than the allowable tensile strength σ_a (which is evaluated similarly as τ_a, but considering the tensile strength); the second formula operates the same check as the first one, but considering shear stresses; finally, the third formula considers the combination of tensile and shear stresses. When FEM simulations are performed to calculate stresses, the von Mises failure criterion [3] is more commonly applied than the above formulas. This criterion is based on the calculation of an equivalent tensile stress – called the von Mises stress – which is compared to the allowable tensile strength σ_a. Of course, in order to satisfy the von Mises criterion, the maximum value of the von Mises stress must be lower than σ_a. Additional failure criteria, including those based on fracture mechanics, are detailed in specialized books [3]. Here, it is worth reminding that the failure criteria check should be always followed by an experimental validation or prototype testing of the final design against real load conditions in the field.

An exemplary application of the failure criteria is shown in Figure 20, illustrating the FEM stress analysis for the case of a bus roof bonding. As noticeable the allowable strengths are compared to the calculated stresses in the points they exhibits maximum values.

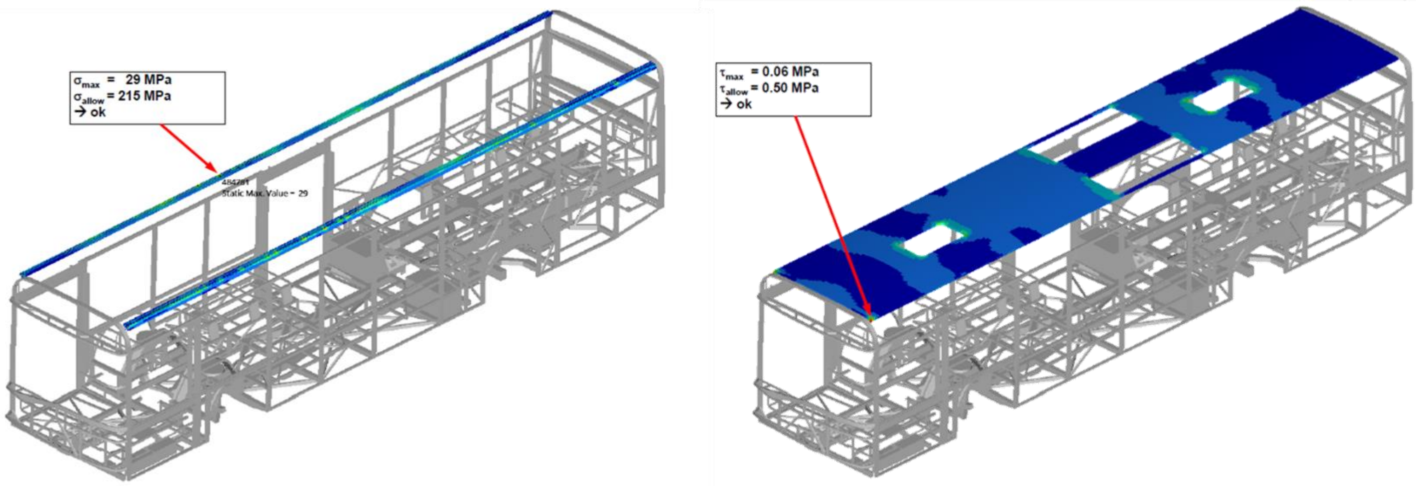


Figure 20 *Stress analysis and failure criteria checks for bus roof bonding application* [7].

2.7 SUMMARY

The general procedure to design bonded joints is schematized in Figure 21 and can be summarized as follows:

1. As a fundamental step, the suitability of using adhesive shall be assessed. This initial phase also includes adhesion tests and characteristic strength measurements on actual substrates at projected application conditions.
2. Draw the preliminary joint geometry, according to the basic principles introduced in section 2.3. The goal is to minimize peel/cleavage and maximize compression/shear. Specific adhesive features, as illustrated in section 2.4, and uniformity of stress distribution in the bondlines shall be also pursued in design draft and joint dimensioning.
3. Identify the boundary conditions related to the operational life of the joint (e.g., maximum service temperature, number of typical load cycles the joint will experience during lifetime, expected environmental aging of adhesives and adherends, etc.).
4. Based on the defined boundary conditions, determine the max allowable strength considering safety factor and adhesive reduction factors, as shown in section 2.5.
5. Calculate the actual max stresses in the joint by analytical or numerical methods (see section 2.6). Failure criteria are then used to compare the calculated stresses to the max allowable strength.
6. Re-design or refine the joint geometry if failure criteria are not met. This step shall be repeated on an iterative manner, so to minimize critical stress concentrations and reach the optimal joint design.
7. Confirm feasibility of final design with real prototypes and validate it with experimental component and large-scale test campaign, before starting production.

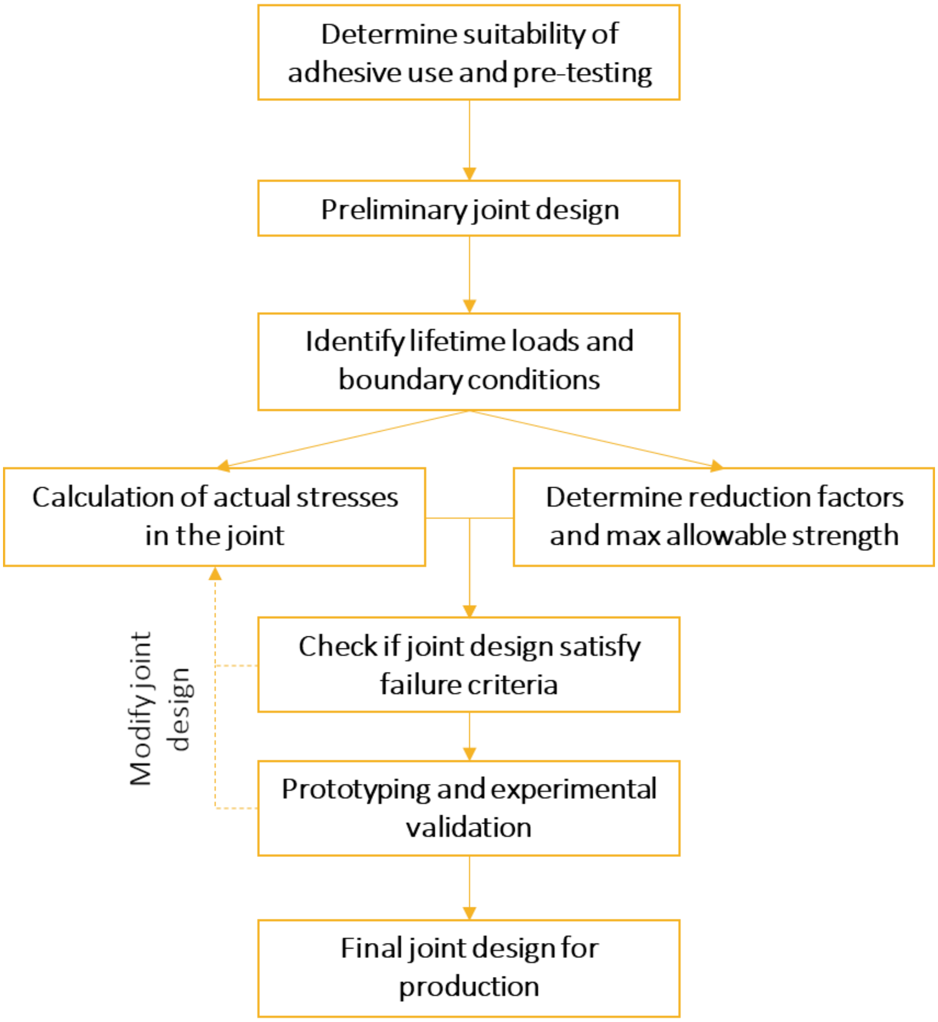


Figure 21 *Procedure to design bonded joints.*

3 ADHESIVE CHARACTERIZATION AND TESTING

This part introduces to the adhesive characterization and lists the main test standards in structural bonding. According to their chemical composition, the most used families of structural adhesives and their corresponding brand names in Sika Industry are:

- Epoxy-based adhesives → SikaPower®
- Polyurethane-based adhesives → SikaForce®
- Acrylic-based adhesives → SikaFast®

The information given in the present guide focuses on two-component (2C) SikaPower®, SikaForce® and SikaFast® adhesives, as well as one-component (1C) SikaPower® adhesives.

3.1 CLASSIFICATION AND REFERENCE CONDITIONS

Sika's structural adhesives can be classified in the following way for application and testing purposes:

- Rigid adhesives: SikaPower® and SikaForce® with elongation at break lower than 40 % at 23 °C
- Semi-rigid adhesives: SikaFast® and SikaForce® with elongation at break higher than 40 % at 23 °C

The curing conditions and bondline thicknesses used by Sika Industry as reference for adhesive tests in structural assembly bonding are listed in Table 1. Technical documentation – such as product datasheets, additional product and technical information, test reports, etc. – based on those reference conditions, unless otherwise specified.

Table 1 *Reference curing conditions and bondline thickness for Sika's structural adhesive testing*.

Product range	Bondline thickness	Reference curing condition	Alternative curing condition
1C SikaPower®	0.3 mm	*Hot curing*: 30 min at 180 °C	None
2C SikaPower®	0.3 mm	*Cold curing*: 7 days at 23 °C / 50 % r.h.	*Warm curing*: 1 h at 80 °C + 24 h at 23 °C / 50 % r.h.
2C SikaForce®	1 mm	*Cold curing*: 7 days at 23 °C / 50 % r.h.	
2C SikaFast®	1.5 mm	*Cold curing*: 7 days at 23 °C / 50 % r.h.	None

IMPORTANT NOTE

Although Table 1 indicates a time of 7 days for cold curing of 2C adhesives, almost all of them would virtually reach full cure (> 80 % reaction completed) already within 1 or 2 days. Table 1 simply indicates the reference conditions for testing purposes in Sika technical documents. In addition, the key technical parameter for production is not the curing time, but rather the time to reach enough strength to be able to move the bonded part without failure. This handling time – more precisely defined in Section 3.3 – usually lay between few minutes to several hours at room temperature, depending on the specific product.

SikaPower® products designed for structural bonding of wind turbine blades are regularly tested with a bondline thickness of 3 mm and cured for 4 hours at 70 °C.

3.2 MAIN TEST STANDARDS

Table 2 summarizes the most used mechanical tests for structural adhesives and the corresponding standards. Due to the type of loading for which structural adhesives are designed, tensile and lap-shear tests are the fundamental tests. In particular, lap-shear tests are preferably performed to characterize adhesion, reactivity and durability by chemical and mechanical aging (e.g., fatigue and creep tests). These tests allow the determination of the reduction factors for engineering design, which have been discussed in Section 2.5 and whose reference testing conditions will be given in Section 3.4.

Table 2 *Main mechanical tests for structural adhesives.*

Test Type	International Standards	Measured properties
Tensile	**ISO 527, ASTM D 638**	**Tensile strength, E-modulus, Elongation at break**
Lap-shear	**ISO 4587, ASTM D 1002**	**Lap-shear strength, Failure mode**
Impact wedge peel	ISO 11343	Impact peel strength, Impact energy absorption
T-peel	ISO 11339, ASTM D 1876	T-peel strength
Floating roller peel	ISO 4578, ASTM D 3167	Floating roller peel strength
Torsion	N.A.	Torsional strength
Pull-off test	ISO 4624, ASTM D 4541	Pull-off strength
Compression	ISO 604, ASTM D 695	Compression Strength
Hardness	ISO 7619, ASTM D 2240	Shore A / D (for semi-rigid / rigid adhesives respectively)
Fracture toughness	ISO 13586, ASTM D 3433	Critical energy release rate (mode I) G_{Ic} Critical stress intensity factor (mode I) K_{Ic}

As a complement to the list of Table 2, additional useful tests are typically carried out to determine thermal and rheological properties of adhesives (Table 3).

Table 3 *Main tests for thermal and rheological adhesive characterization.*

Test Type	International Standards	Measured properties
DMA*	ISO 6721, ASTM E 1640	Glass transition temperature*, Storage modulus, Loss factor
Density	ISO 1183	Density at room temperature (RT)
Viscosity	ISO 3219, ASTM D 1084	Viscosity at RT and at constant shear rate of 10 s^{-1}

* DMA = Dynamic Mechanical Analysis: reference tests are performed by Sika in torsion mode with frequency of 1 Hz and ramp rate of 5 °C/min. The glass transition temperature is measured at the loss factor peak.

3.2.1 TENSILE TESTS

Various specimen sizes and testing conditions could be employed for tensile tests according to ISO 527. The aforementioned classification between rigid and semi-rigid adhesives is conveniently used by Sika Industry to define reference conditions as shown in Table 4. Typical test results obtained for the various types of adhesives are illustrated in Figure 22.

Table 4 *Sika tensile test conditions.*

Adhesive Type	Specimen type	Test speed	Elongation range for E-modulus
Rigid	Type 1B acc. to ISO 527	1 mm/min	0.05 – 0.25 %
Semi-rigid	Type 5A acc. to ISO 527	200 mm/min	0.05 – 0.25 % or 0.5 – 1 %*

* The reference range is 0.05 – 0.25 %, the alternative range 0.5 – 1 % is optionally used for additional information

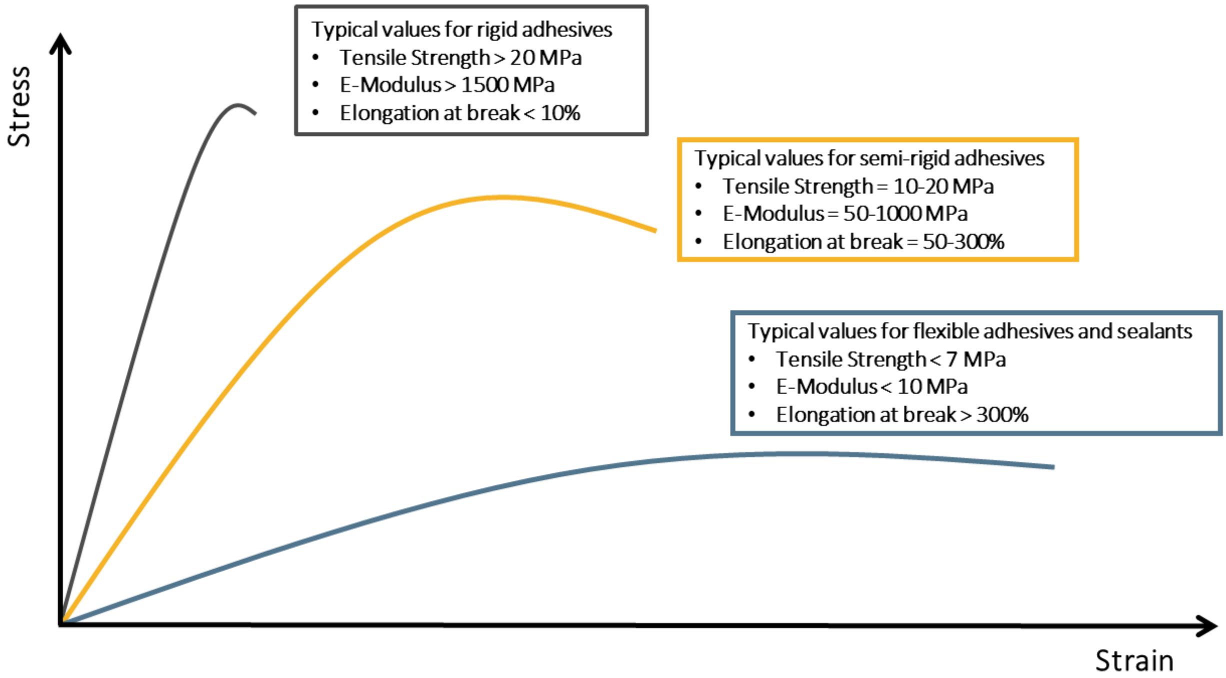


Figure 22 *Specimen types for tensile tests.*

Besides tensile properties like strength, modulus and elongation at break, the Poisson's ratio v can be also measured through tensile tests (for accuracy reasons, only with the thickest specimen type 1B). Under assumption of isotropy, measurements of E-modulus and Poisson's ratio additionally allow the estimation of the G-modulus (shear modulus) as: $G = E / (2 + 2v)$.

3.2.2 LAP-SHEAR TESTS

The reference international standards for lap-shear tests are ISO 4587 and DIN EN 1465 or ASTM D 1002: they prescribe a specimen size as shown in Figure 23 and a nominal bonded area is 25 mm x 12.5 mm. The reference bondline thickness recommended by Sika depends on the product range as in Table 2. Moreover, for product datasheets and API, Sika Industry Technical Department carries out lap-shear tests using the reference substrates and pre-treatments listed in Table 5.

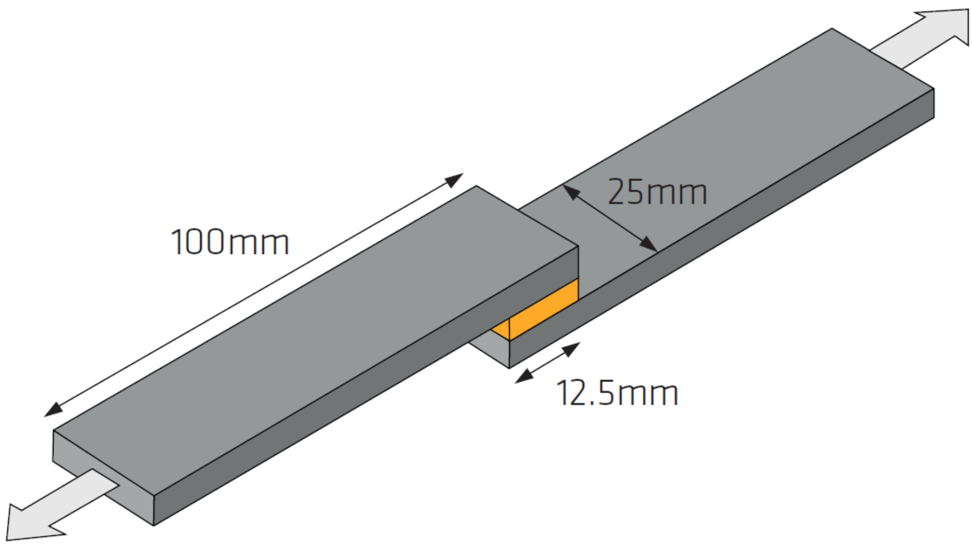


Figure 23 *Specimen size for lap-shear tests.*

Table 5 *Reference substrates and pre-treatments for lap-shear tests.*

Product range	Reference Substrate	Substrate ID	Pre-treatment
SikaPower®	5 mm-thick mild steel*	S235JR+C EN10027-1	Grinding + Sika® Cleaner P
SikaForce®	2 mm-thick e-coat steel	DC04 with BASF CathoGuard®800	Sika® Cleaner P
SikaFast®	2 or 6 mm-thick aluminum	EN AW 5754 H22	Sika® ADPrep

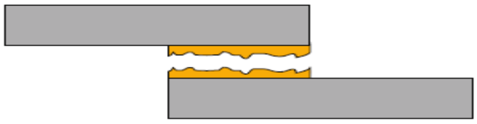
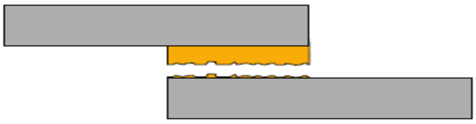
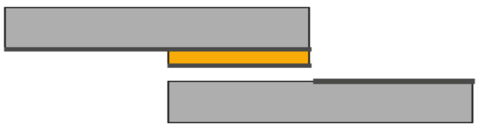
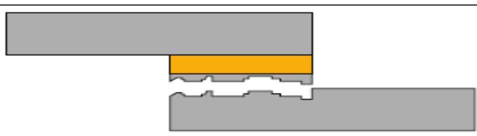
*Product datasheets of 1C SikaPower® adhesives refer to different steel types and thickness.

IMPORTANT NOTE

The substrates, pre-treatments, testing and curing conditions indicated in this document are for reference only. Sika Industry Technical Department performs specific adhesive tests based on particular customer specifications and substrates as a part of technical service support.

As far as the evaluation of the failure mode is concerned, ISO 10365 and the Technical Code DVS 3302 [8] are normally used as reference. The failure may occur within the adhesive layer, in the adherends or at the interfaces between adhesive and adherends; Table 6 details failure mode designations and schematics.

Table 6 *Failure mode designations in lap-shear tests.*

Failure location	Designation	Schematic	Note
Within the adhesive layer	Cohesive Failure (CF)		Both adherends show an adhesive layer
	Surface-close Cohesive Failure (SCF)		A thin layer of adhesive lays on one adherend
	White Failure (WF)		High force transfer cause stress whitening damage of the adhesive
At the interface adhesive/adherend	Adhesive Failure (AF)		No adhesive residue on one surface and no discoloration of adhesive
	Corrosion (COR)		Visible corrosion of the adherend surface
In the adherend	Coating Rupture (CR) or Delamination Failure (DF)		Break of the coating layer or delamination of an adherend
	Substrate Failure (SF)		Break of an adherend (occurring in substrate bulk or near to the joint)

White failure (WF) can occur e.g. when bonding metals with high-strength epoxy adhesive: due to the transmission of elevated forces within the joint, the adhesive polymer can get damaged close to the substrate interface and get a whiter or lighter color, while the metal surface is visually bare without adhesive residues. This type of failure differs from the classic adhesive failure (AF), since in the latter case the adhesive surface is glossy and does not show any discoloration (its color is similar to the adhesive excess on the sample and is darker than in CF or WF, as in Figure 24).

It is important remarking that failure patterns with structural adhesives show often intermediate characteristics among the ones illustrated in Table 6; these situations are referred to as mixed failures and are expressed with percentage of each failure type described in the table. Obviously, the failure should preferably occur within the adhesive layer (CF, SCF or WF), so that the joint design can entirely rely on the adhesive properties. However, mixed or other failure types may also be accepted for structurally bonded joints, depending on the specific applications and on the measured average joint strength as well as the repeatability of the results (measured standard deviation).

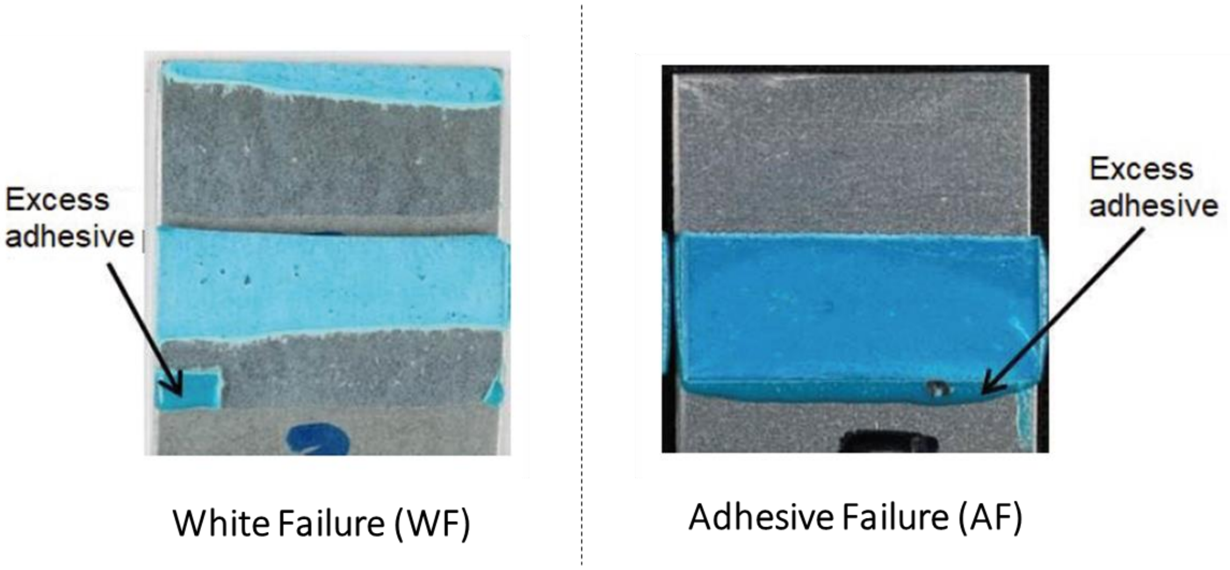


Figure 24 *Difference between white failure (WF) and adhesive failure (AF) as in Technical Code DVS 3302* [8].

3.2.3 PEEL TESTS

Well-designed joints minimize peeling as seen in Section 2.3, but it is hard to eliminate peel forces entirely. Specific tests enable design engineers to check the prescribed peel forces do not exceed the peel resistance of the adhesive. T-peel and floating roller peel tests are standardized tests, generally performed at a rate of 100 mm/min for metal adherends. T-peel strength is more commonly measured, while floating roller peel tests are carried out when one of the adherends is flexible.

Another widespread type of peel test is the impact wedge peel test, which is usually performed at a rate of 2 m/s, namely a very fast speed compared to other tests. Therefore, it provides information not only on the peel resistance of an adhesive, but also on its capacity to withstand dynamic forces at high speed and to absorb energy until crack initiation and propagation. In this sense, impact wedge peel tests represent quick measurements of the adhesive toughness and are complementary to cyclic fatigue tests and longer fracture toughness tests. Sika reference substrate for impact wedge peel tests is electrogalvanized steel DC04 ZE75/75 EN10130 with 0.8 mm thickness (Figure 25).

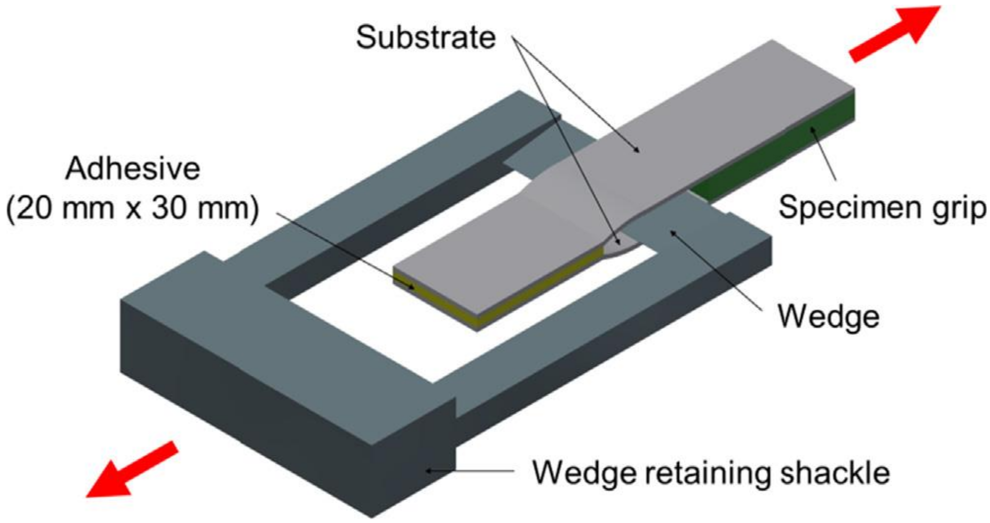


Figure 25 *Impact wedge peel test set-up.*

3.2.4 TORSION AND PULL-OFF TESTS

Torsion and pull-off tests are occasionally performed as an alternative to lap-shear tests. Due to the lack of international standardization of torsion and pull-off measurements for adhesive materials, the use of these tests is typically limited to checking the adhesion on substrates that are difficult to prepare in the form of a lap-shear specimen (Figure 23).

The torsion tests are conducted at speed of 10 °/min using cylindrical aluminum dollies (with inner diameter of 15 mm and outer diameter of 25 mm) and a reference adhesive thickness of 1 mm, which makes these tests generally unsuitable for rigid epoxy adhesives. The pull-off tests are conducted at rate of 0.2 MPa/s according to the standard for coatings ISO 4624 or ASTM D 4541, using single aluminum dollies with diameter of 20 mm. Note that dollies for both torsion and pull-off tests should be opportunely pre-treated, depending on the tested adhesive.

3.3 REACTIVITY TESTS TO DETERMINE OPEN TIME AND HANDLING TIME

As above mentioned, lap-shear tests are commonly carried out to assess reactivity and durability or aging performance of adhesives. Reactivity tests regard the determination of open time and handling time.

Open time tests are normally performed by applying the adhesive on lap-shear specimens (typically by one-side applications) and close the assembly at subsequent times from the application. After full cure, lap-shear strength and failure pattern are measured. The open time is defined by the maximum time for closing the assembly, at which full lap-shear strength (datasheet value) is reached with cohesive failure. Note that the described open time measurement is different from a pot life test as defined by ISO 10364 or ISO 9514.

In the case of handling time tests, lap-shear specimens are bonded immediately after adhesive application and tested at defined subsequent times before full cure. The handling time is defined as the minimum waiting time, at which a standard threshold lap-shear strength of 1 MPa is reached. Of course, lower strength thresholds can be used, upon indication. Note that both open time and handling time tests are performed at set temperature and relative humidity (normally 23 °C / 50 % r.h.), since those parameters have significant influence on the results. Depending on the product, the bead size and the substrate type may also strongly affect the results.

IMPORTANT NOTE

Comparing handling times – like any other characteristic time – from datasheets of different adhesive manufacturers can be largely misleading. Due to the lack of defined standard, each manufacturer can set a different threshold for the measurement, as well as different other influencing parameters can be chosen.

3.4 AGING AND DURABILITY TESTS TO DETERMINE REDUCTION FACTORS

Long-term durability tests are divided in: (a) chemical or environmental aging resistance, including temperature resistance, and (b) mechanical aging resistance tests. In both cases, lap-shear tests are performed, and the adhesive resistance is determined as percentage of strength loss (reduction factor) comparing the results before and after aging, as exemplary shown in Figure 9.

3.4.1 CHEMICAL AND ENVIRONMENTAL AGING

These tests are carried out exposing the cured lap-shear samples at harsh chemical or environmental conditions for a given amount of time or according to a prescribed aging cycle. After exposure, the samples are reconditioned for minimum 2 hours at 23°C / 50% r.h. and then tested. The residual strength, expressed as a percentage of initial strength before exposure (reference), indicates the aging resistance and can be used as a reduction factor for designing purpose as seen in Section 2.5. Note that, although the samples undergo artificial aging in harsh conditions, the test results do not predict the natural aging in real life operation: no accelerated aging cycle can guarantee comparable results to any years of service life, although it gives an indication of the adhesive resistance to specific external conditions or environments. The most used chemical and environmental aging conditions are summarized in Table 7.

Table 7 *Reference chemical and environmental aging conditions.*

Aging Test Type / Chemical Environment	Reference Temperature	Reference Duration	Reference Int. Standard
Exposure at 200 °C in oven	200 °C	1 hour	N.A.
Exposure at 100 °C in oven	100 °C	30 days	N.A.
Cataplasma test (70 °C / ~98 % r.h.)	70 °C	30 days	ISO 17194
Deionized water	23 °C	30 days	ISO 17194
Deionized water	90 °C	30 days	ISO 17194
Isopropyl alcohol (IPA)	23 °C	30 days	ISO 17194
Unleaded gasoline (ISO 1817, standard fuel liquid 2)	23 °C	30 days	ISO 17194
Motor oil (ISO 1817, oil 3)	23 °C	30 days	ISO 17194
Acetic acid 10 %	23 °C	30 days	ISO 17194
Sodium hydroxide 35 %	23 °C	30 days	ISO 17194
Ethylene glycol 50 %	23 °C	30 days	ISO 17194
Sodium chloride 5 % (seawater simulation)	23 °C	30 days	N.A.
DVS 1618 cycle (acc. to Sika CQP 034-1: B+C+F+G+L)	**variable**	**1 cycle (22 days)**	**DVS 1618**
PV 1200 (humidity and thermal shock test)	variable	56 cycles (28 days)	VW Standard
PV 1210 (salt spray and condensation test)	variable	30 cycles (30 days)	VW Standard
VDA 233-102 cycle	variable	6 cycles (6 weeks)	VDA 233-102

Combination of test types in Table 7 are also used as reference, for example 3 cycles consisting of PV 1200 for 1 week followed by PV 1210 for 3 weeks (total 3 months). In the view of external application, exposure to UV light for 1000 hours or artificial weathering are performed. For certain plastic substrates (e.g. ABS), environmental stress cracking tests might be complementary needed.

3.4.2 MECHANICAL AGING

Mechanical aging regards the exposure of the joint to continuous static or dynamic forces that induce real life stresses in the adhesive. The goal here is not to test the ultimate strength, but rather to assess the maximum stress levels that the material can withstand for prolonged time periods. Characterizing the relation between applied load and applied time or number of load cycles allows obtaining realistic values for long-lasting joint design. Mechanical aging tests can be differentiated in creep tests, when the applied forces are constant over time, and in fatigue tests, when the applied forces are dynamic (specifically cyclic).

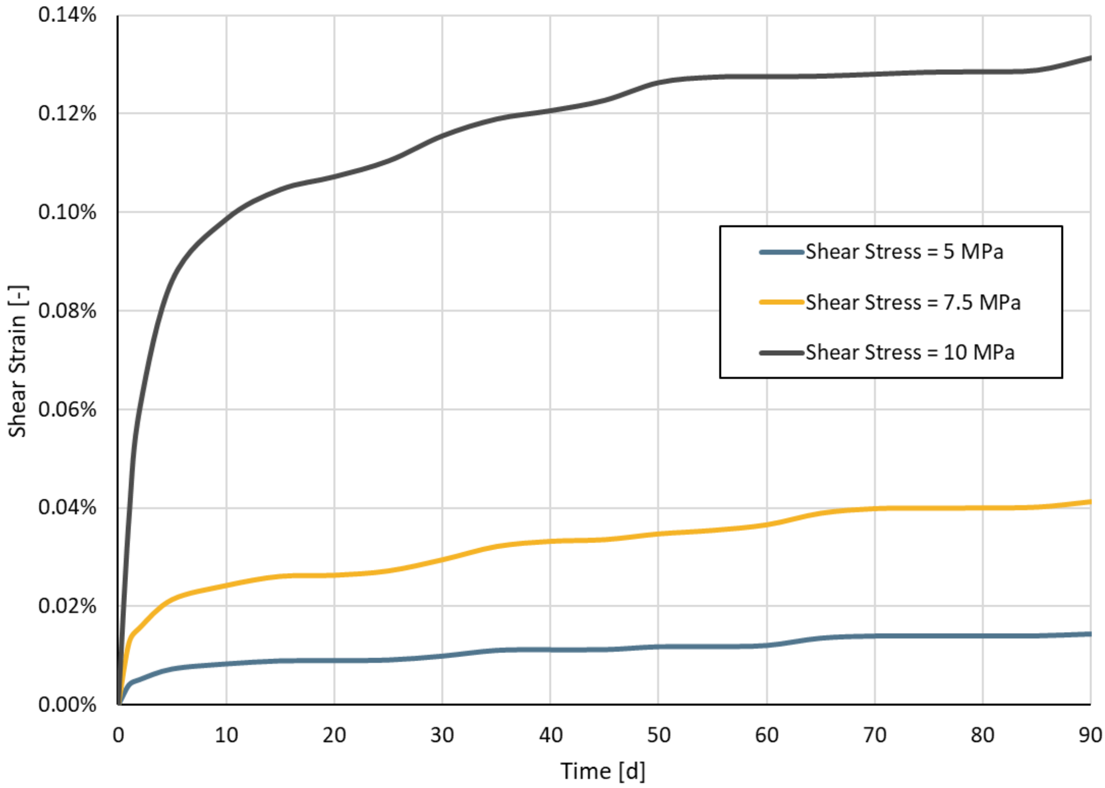


Figure 26 *Exemplary creep curves for SikaPower® epoxy adhesive.*

The creep tests are regularly performed by applying dead loads to lap-shear specimens in vertical position and recording the joint displacements over time. If the dead loads are too heavy to manipulate, special test set-ups using levers, springs or universal testing machines can be employed instead. Concerning Sika's reference conditions, different stress levels are tested for 90 days at 23 °C / 50 %. Normally, the tested maximum stress corresponds to about 20 % (for rigid products) or 10 % (for semi-rigid products) of the ultimate strength. The samples that survive the creep tests are unloaded and recovered for 7 days at RT, afterward, their lap-shear strength is tested again, in order to determine reduction factors compared to reference non-crept samples. As a result, Sika provides those reduction factors and curves of creep deformation over time at various stress levels (Figure 26). It is here worth highlighting that rigid, high-strength epoxy adhesives show typically elevated resistance to creep loading, as noticeable by the negligible shear strain displayed by Figure 26.

The fatigue tests are performed according to ISO 9664. The applied stresses are cyclic (Figure 27) and the reference ratio of minimum to maximum stress is R = 0.1. The reference frequencies of the stress cycle are 20-30 Hz for rigid products and 10-20 Hz for semi-rigid products. Sika performs fatigue tests up to a maximum of 10 million cycles and provides curves of maximum stress vs. number of cycles (S-N curves or Wöhler curves) according to ISO 12107. From a S-N curve (example in Figure 19), it is possible to derive limits of endurance and corresponding reduction factors at given numbers of cycles, as seen in Section 2.5.

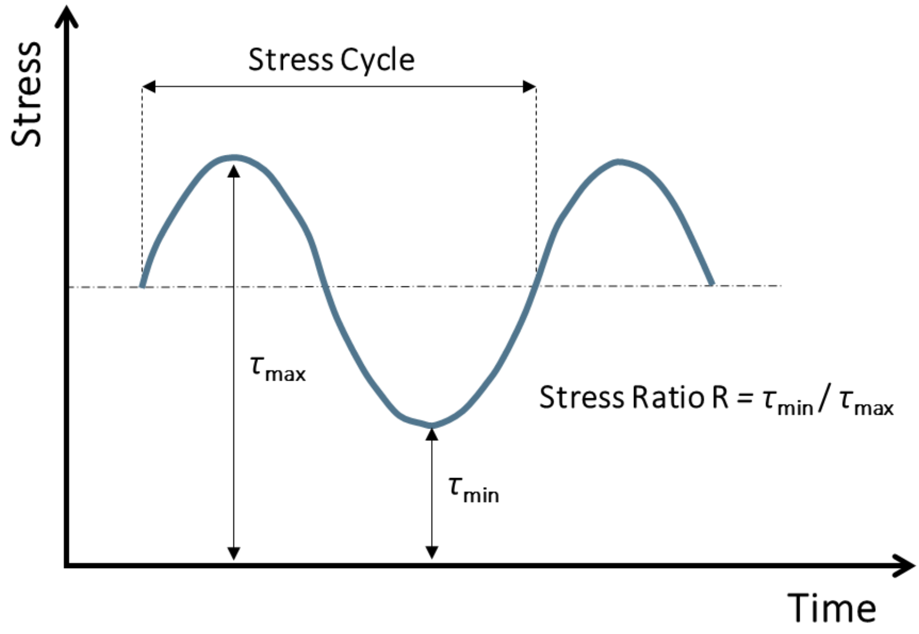


Figure 27 *Cyclic stress in fatigue tests.*

3.5 TEST SERVICE WORKFLOW

The above information on material characterization tests is helpful to verify the suitability of an adhesive for a new structural bonding application. The following list enumerates the exemplary steps of a typical test service workflow:

1. Define goals and plan of the test campaign based on the foreseen application. Normally, the first check includes the determination of the strength and adhesion on actual substrates at expected application conditions. Thus, the test plan must detail not only the adhesive products and type of tests to carry out, but also all substrates information, surface treatments and pre-treatments, bondline size and thickness, curing conditions, etc.
2. Carry out initial adhesion tests. As industry standard for structural bonding applications, the adhesion check is ideally performed by simple lap-shear tests (see Section 3.2.2). For this purpose, the substrate samples must be produced or cut as shown in Figure 11. If lap-shear tests are not practicable for any reason, torsion or pull-off tests (see Section 3.2.4) could be alternatively performed in absence of other references.
3. Collect and interpret the test results. A useful resource in this regard is the Technical Code DVS 3302 [8]. As aforementioned, depending on the substrate characteristics, structural adhesives may often show mixed failure modes. Thus, failure mode evaluation is always accompanied by measurements of actual strength and relative standard deviation, which must be compared to application specifications.
4. Define and carry out tests that simulate lifetime aging behavior of the joint for the intended application. The references of Table 7 can guide the selection of suitable aging cycles, according to the expected chemical or environmental exposure. For example, tests in a salt spray chamber (as in PV 1210) would give an indication of the material performance in the case of potential corrosion. In absence of particular references, the DVS 1618 cycle is typically suggested by Sika Industry for assembly bonding application.
5. Finally, additional or special tests can be considered and performed according to further standards or specifications. Normally, full component or prototype testing follows the basic adhesion and material characterization tests of the points above.

4 STRUCTURAL ADHESIVE TYPES AND SELECTION CRITERIA

The above chapters have already introduced the two main criteria for adhesive selection:

- Their mechanical characteristics, which must fit the application requirements regarding loads and durability
- Their adhesion and appropriateness to bond specific substrates

Regarding the last point, it has been shown that the adherents' stiffness shall guide the adhesive choice. For example, it is not convenient to bond flexible substrates with rigid adhesives. Similarly, it would not make sense to use high strength adhesives on coated or primed surfaces, because coatings and primer layers form weak interfaces that limit the joint strength.

In this chapter, the discussion of adhesive selection criteria is extended, starting from a review of the main adhesive chemistries and technological properties.

4.1 CHARACTERISTICS OF ADHESIVES BASED ON CHEMICAL TECHNOLOGIES

Although an adhesive is properly chosen for a given application on the base of its specific properties rather than the generic properties of the family it belongs to, it is useful to give an overview of the main characteristics of basic structural adhesive chemistries for the purpose of a quick comparison and shortlisting. Note that most Sika products have a hybrid formulation, in which the base chemistry (epoxy, polyurethane, acrylic) has been engineered to enhance curing and material properties.

4.1.1 EPOXY-BASED ADHESIVES

Epoxy-based adhesives show naturally high strength and stiffness. They can normally bond a variety of substrates and have good environmental and temperature resistance. For these reasons, they are mainly indicated to bond bare metals (particularly high strength steel or aluminum alloys) or structural composites (e.g., CFRP, GFRP).

Two main types of epoxy-based adhesives are identified: 1C or hot-curing epoxies and 2C or cold-curing epoxies. Hot-curing epoxies often find applications in the assembly of body-in-white vehicle components. Here, these adhesives are applied on preformed metallic parts, whose surfaces are often non-treated and oily, and later cured in ovens at high temperatures (ordinarily greater than 150 °C), following the e-coating or powdercoating process.

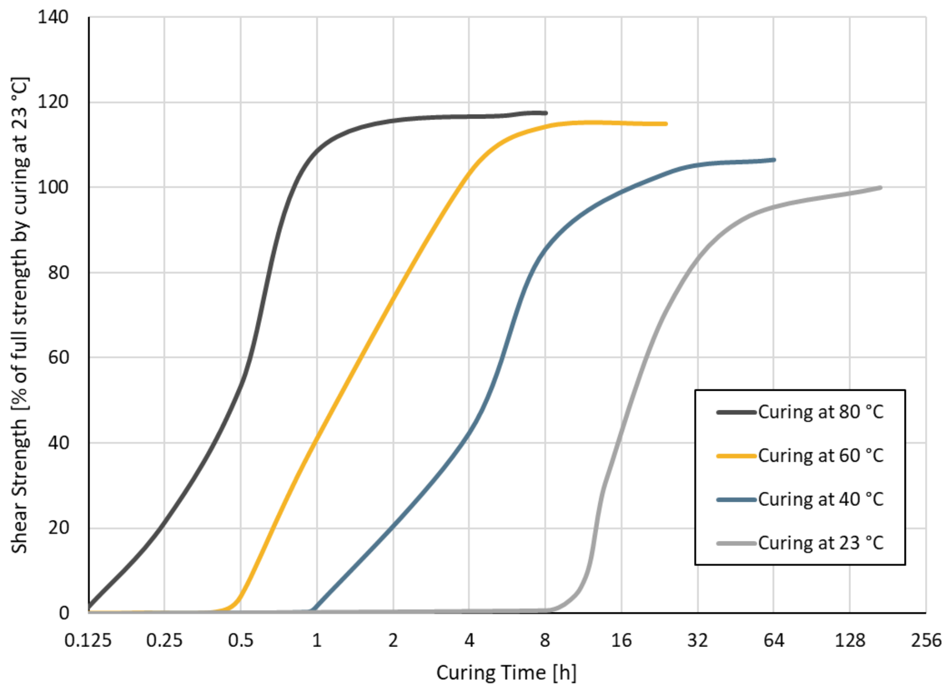


Figure 28 *Exemplary strength build-up of 2C epoxy at various curing temperatures.*

Cold-curing epoxies instead cure by mixing the two components and do not need heat to trigger the curing reaction. Nevertheless, if these products are exposed to warm conditions during curing, the reaction is faster and higher strength and glass transition temperature can be achieved (Figure 28). This is a consequence of higher energy available in the warm external environment, which is stored in the adhesive system in the form of more and stronger chemical bonds. Note that a similar result is obtained if the epoxies are post-cured, namely they are exposed to a warm environment after initial curing in cold conditions.

Unlike 1C epoxy adhesives, 2C epoxies cannot bond oily surfaces and require the substrates to be clean, dry and free from dust and grease, like all 2C adhesives in general. The use of a solvent cleaner – such as heptane, isopropanol, acetone or similar chemicals, depending on the nature of the substrates – is often sufficient to clean the adherends. To achieve maximum strength, it is typically recommended to abrade or grind the surfaces to bond, so to remove the weak layers (such as the oxide layer over aluminum alloys) or eliminate residuals from substrate manufacturing (for example residuals of release agents for molded composites). Some 2C epoxies may require two-side application i.e., on both adherends to bond – to achieve maximum open time (if so, the datasheet indicates it explicitly). Bonding activators and primers are commonly not used with epoxies, because they can form a weak interfacial layer between adhesives and substrates, although exceptions are possible depending on the specific case.

In terms of mechanical properties, 1C epoxies show higher performance than 2C adhesives and are nowadays available many formulations that maximize durability and crash resistance, keeping at the same time high stiffness and strength. Conversely, 2C epoxies are inherently more brittle than 1C adhesives, although toughened 2C systems have been introduced for industrial use. In this context, Sika has developed a new generation of toughening agents, which allow 2C adhesives to bridge the performance gap with 1C epoxies. This technology is called SmartCore [9, 10] and enables the formulation of 2C epoxies with impact peel strength of 20-30 N/mm, while standard toughened 2C epoxies – laying in the same range of tensile strength and stiffness – show an impact peel strength lower than 12 N/mm (Figure 29). The increased toughness level given by the SmartCore technology translates also into higher resistance to fatigue and dynamic loads, which are traditional weaknesses of epoxies.

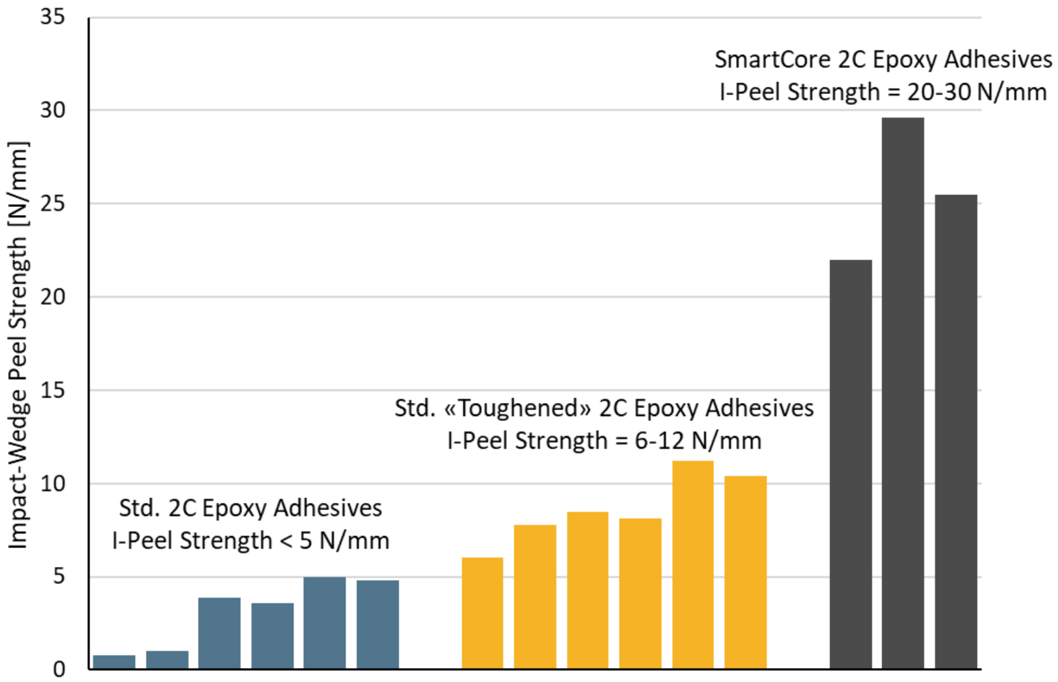


Figure 29 *Comparison of impact-wedge peel strength of standard, toughnened and SmartCore 2C epoxies.*

4.1.2 POLYURETHANE-BASED ADHESIVES

Polyurethane-based adhesives used for structural bonding applications are typically 2C systems, which do not require heat or air humidity to cure. These adhesives are available in a variety of formulations, going from rigid to semi-rigid or even flexible products. As an example, the elastic modulus range can extend from about 10 MPa to more than 1500 MPa. Their mechanical strength and stiffness are usually lower than epoxies, while their flexibility and ability to accommodate peel forces can be reasonably high. For these reasons, polyurethanes are frequently employed to fill gaps or to bond dissimilar materials. Nevertheless, these adhesives show a narrower adhesion range than epoxies and would require specific chemical (activators and/or primers) or physical (plasma/flame) pretreatments of the surfaces to bond. Without other pretreatments than surface cleaning, polyurethanes can generally just adhere on coated metals – e.g., e-coated, powdercoated or painted metals (note: not anodized aluminum) – and on composites like CFRP, GFRP, SMC, etc., depending on the matrix resin.

While flexible polyurethanes show relatively stable mechanical properties over a large temperature range, typical structural 2C polyurethanes exhibit a strong temperature-dependent behavior. They are normally brittle at low temperatures, whereas they lose mechanical strength and stiffness at high temperatures. This is the consequence of a glass transition occurring within the usual service temperature range. This common limitation of structural 2C polyurethanes can be overcome by the Powerflex technology [10, 11]. SikaForce® adhesives based on the Powerflex technology are characterized by a Tg lower than -40 °C. Thus, they show good flexibility at low temperatures as well as higher strength and stiffness then standard 2C polyurethanes at high temperatures (Figure 30).

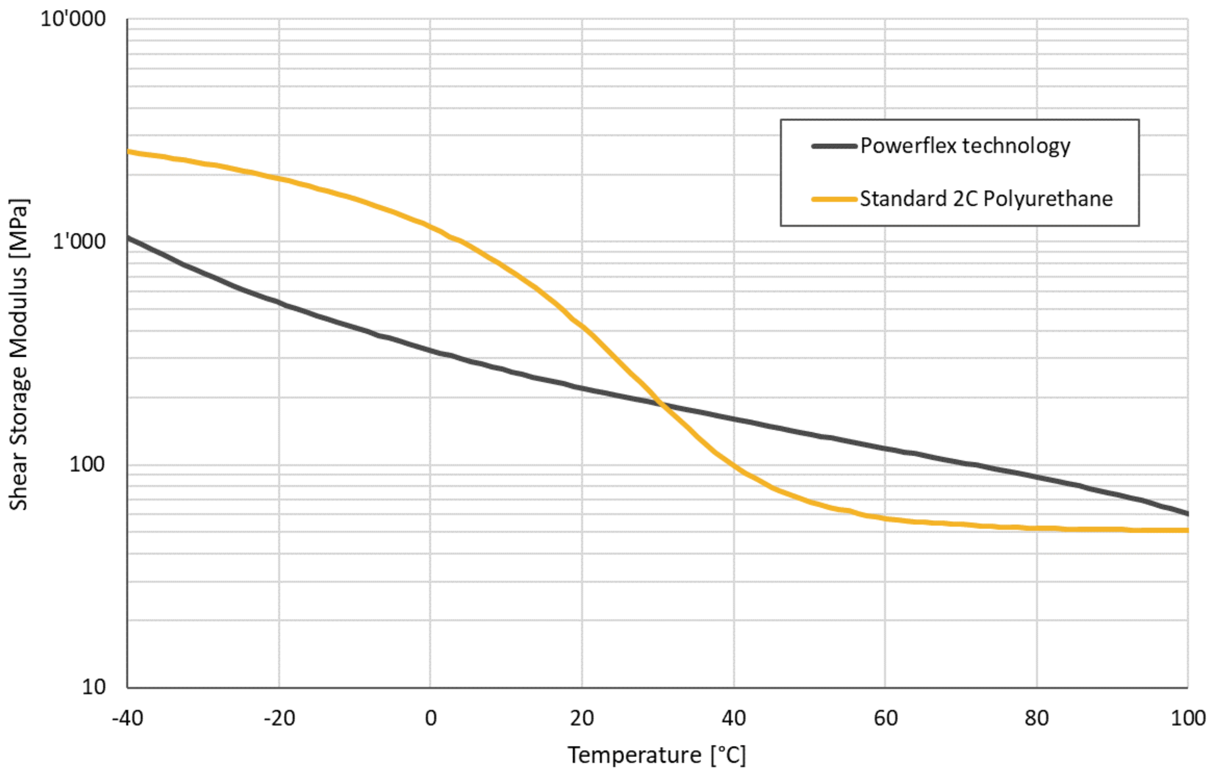


Figure 30 *Comparison of shear modulus of Powerflex technology and a standard 2C polyurethane from DMA tests.*

Besides the mechanical properties, the curing characteristics of 2C polyurethanes can also cover a wide range. Both fast and slow curing adhesive systems are available, showing short and long open times respectively. In practice, fast curing systems are preferred, because they reduce the idle time to wait until the adhesives reach enough strength, so that the bonded joints can be handled and moved to the next manufacturing step. Yet, fast adhesives have naturally short open or working times, which may not suit the needs of the production department: imagine for example the case of bonding large structures like bus roofs or ship decks. To increase productivity without needing to heat up the joints, but keep a long enough adhesive workability, Sika has introduced the innovative Curing by Design technology [11]. This technology – which can be combined to the abovementioned Powerflex in the same products – enables the optimization of the open time to the application requirements and, concurrently, the minimization of the idle time to reach handling strength. As shown by Figure 31, the curing reaction of an adhesive with Curing by Design technology develops immediately at the end of the working time and is considerably faster than a standard 2C polyurethane with same working time.

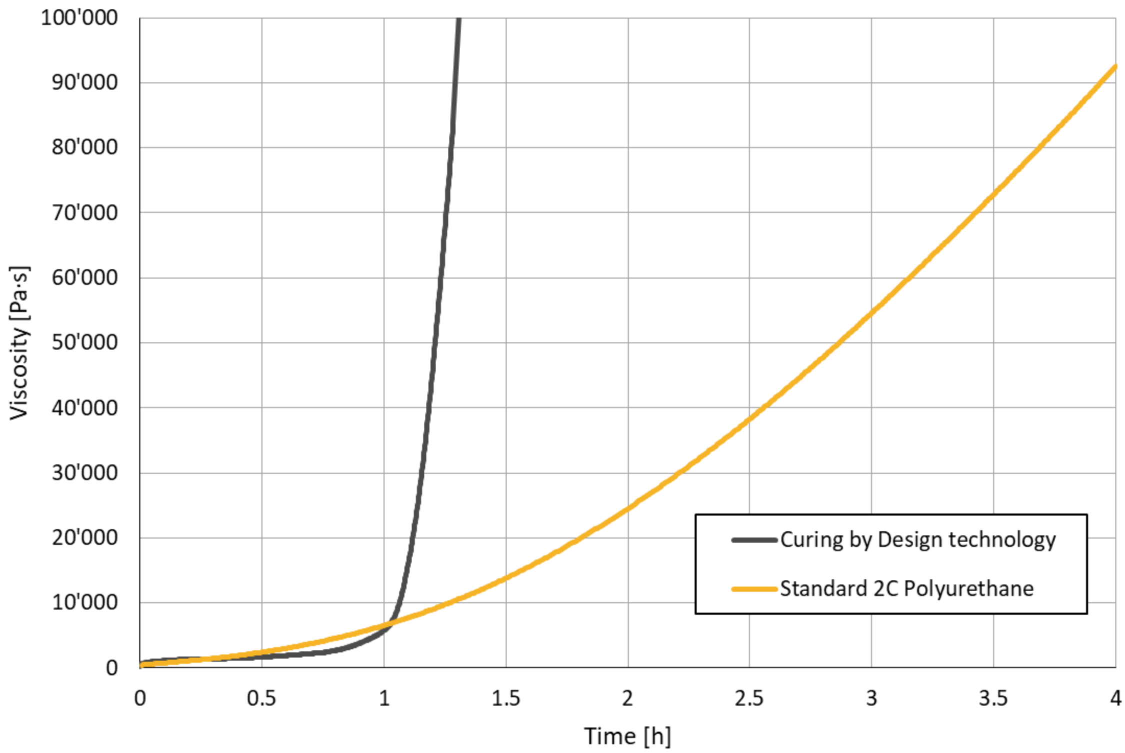


Figure 31 *Comparison of curing behavior of Curing by Design technology and a standard 2C polyurethane with same working time.*

4.1.3 ACRYLIC-BASED ADHESIVES

Acrylic-based structural adhesives are mostly 2C semi-rigid products, characterized by good levels of tensile/shear strength as well as large flexibility, toughness and resistance to peel. At room temperature their mechanical performances are typically comparable to (non-rigid) 2C polyurethanes, but they show a larger adhesion spectrum, being able to bond several types of metals, composites, glasses, woods, most plastics, etc. Good adhesion can be often achieved by only surface cleaning and without further pretreatments, although surface abrasion and/or the use of apposite activators can be beneficial for bond durability, particularly on specific metals or rubbers.

Besides mechanical and adhesion properties, the main feature of acrylics is their fast curing reaction. These adhesives develop handling strength within minutes from bead application and rapidly reach full cure (Figure 32). For this reason, they are the preferred option for quick fixations. However, the heat generated by their exothermic curing reaction is high. In order to avoid elevated temperature peaks, which can damage the substrates beneath, it is commonly recommended to limit the adhesive layer thickness. Other critical aspects to consider when working with acrylics are their typical strong smell and relatively high shrinkage during curing. It is worth remarking also that strength and flexibility of acrylic-based adhesives are generally sensitive to temperature changes, namely these adhesives are prone to embrittlement at low temperatures and strength loss at high temperatures.

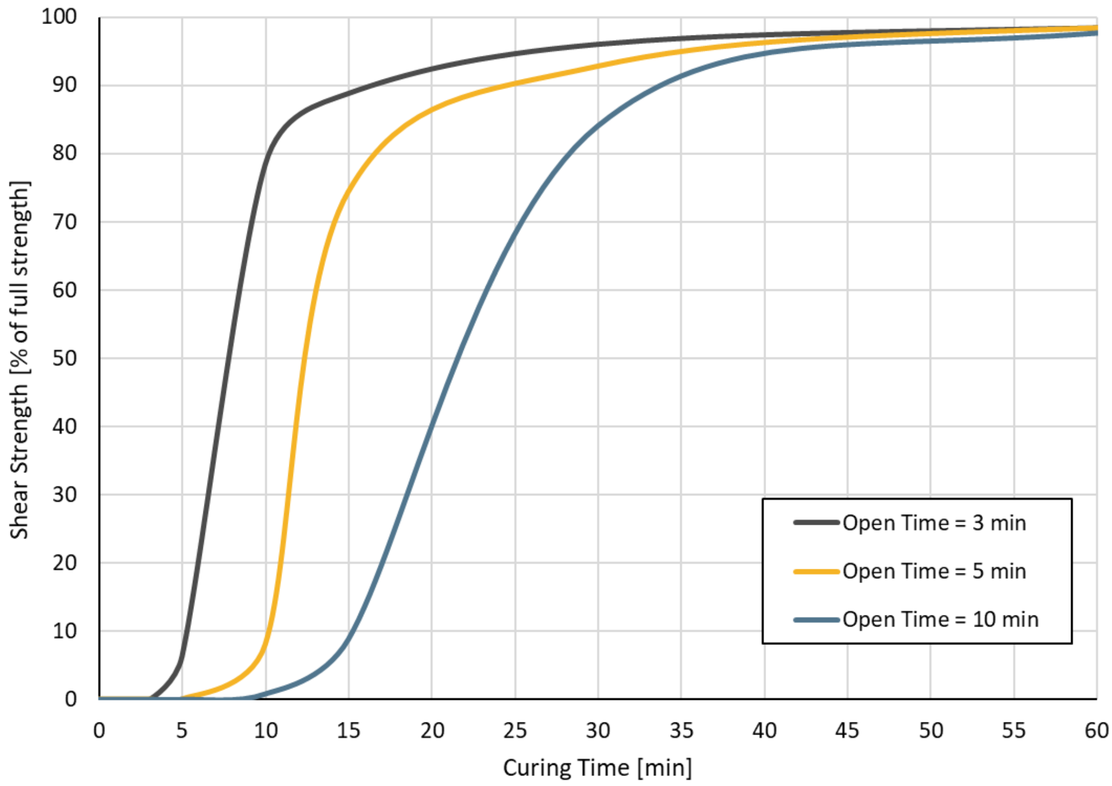


Figure 32 *Exemplary strength build-up of 2C acrylic-based adhesives.*

4.2 TECHNOLOGICAL PROPERTIES AND PRACTICES IN INDUSTRIAL APPLICATIONS

Table 8 summarizes the characteristic properties of structural adhesives sorted by chemical families. The table is only given for indicative reference and comparison at a glance. Sika provides specific information and measured values for single adhesives in technical documents like product datasheets and API.

Despite of the differences listed in Table 8, Sika structural adhesives for industrial use share common features regarding their practical application. In general, they show a thixotropic paste consistency with more or less pronounced non-sag behavior. Their viscosities vary with temperature (Figure 33) and the optimal application temperatures usually range from 15 °C to 35 °C (note: 1C epoxies may require higher application temperatures). Within this range, neither the adhesives are too liquid, nor their viscosities are too high and demanding elevated forces for extrusion. If the ambient temperature in production is low, the adhesive material could still be extruded out of cartridges, after warming them up at 30-40 °C. In the case of application out of bulk packaging such as pails or drums, the dispensing equipment – or at least its terminal part including hoses, dosing unit and nozzle or mixer – can be heated to enable the extrusion of highly viscous adhesives after specific verification.

Table 8 *Indicative characteristics of structural adhesives for industrial applications.*

Characteristics	1C & 2C Epoxies SikaPower®	2C Polyurethanes SikaForce®	2C Acrylics SikaFast®
Typically used for bonding	Metals (uncoated), Composites	Metals (coated), Composites	Various types of substrates
Tensile/Shear Strength	High – Very high	*Rigid*: Medium – High *Semi-rigid*: Low – Medium	Medium
Elongation	Low	*Rigid*: Low *Semi-rigid*: Medium - High	Medium
Peel Strength	*Regular*: Low *SmartCore*: Medium – High	*Rigid*: Low *Semi-rigid*: High	Medium – High
Impact Resistance and Toughness	*Regular*: Low *SmartCore*: High	*Regular*: Medium *Powerflex*: High – Very high	Medium – High
Fatigue and Creep Resistance	*Regular*: Medium - High *SmartCore*: Very high	Medium	Low
Max service temperature	Above 120 °C	100 °C	80 °C
Mechanical Performances at High/Low Temperatures	High	*Regular*: Low – Medium *Powerflex*: Very High	Low – Medium
Heat Resistance	High	Medium	Medium
Chemical Resistance	High – Very high	Medium – High	Medium – High
Curing at room temperature	*1C Systems*: No *2C Systems*: Yes	Yes	Yes
Working time	Long	Variable, short to long	Short
Curing speed	*At room temperature*: Slow *In warm/hot conditions*: Fast	*Regular*: Slow – Medium *Curing by Design*: Fast	Fast - Very fast

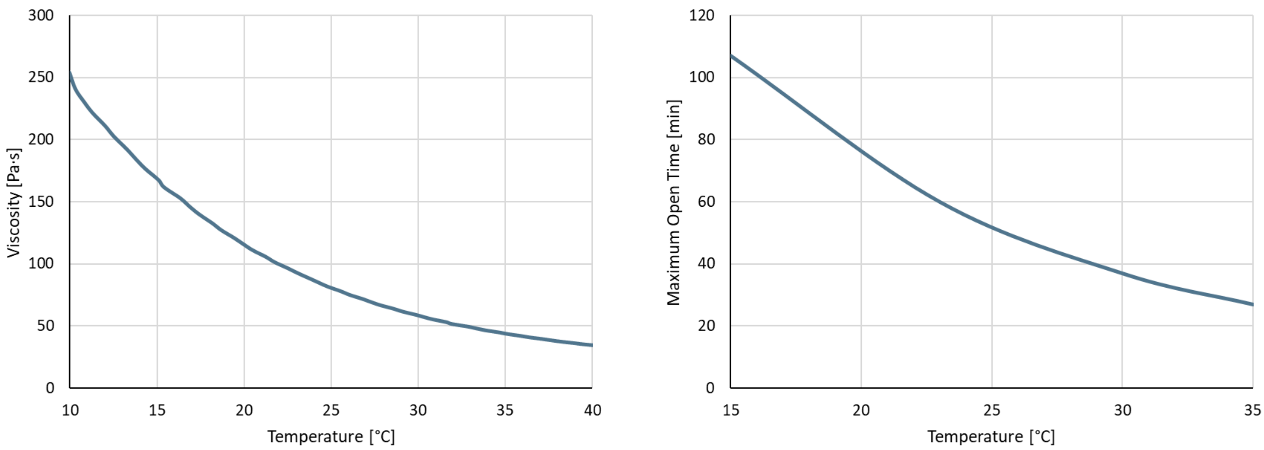


Figure 33 *Exemplary viscosity and open time as function of application temperature.*

As Figure 33 illustrates, the temperature influences the working or open time, besides the viscosity. As a rule of thumb derivable by Arrhenius equation [12], any variation of 10 °C changes the working time by a factor of 2: namely, if the temperature increases by 10 °C, the working time halves; if the temperature decreases by 10 °C, the working time doubles. Similarly, this rule of thumb could be applied for handling and curing times. Note that high humidity can also reduce the working time, especially in the case of non-rigid polyurethanes with long open times (Figure 34). Finally, the bead size may have an influence as well (as also shown by Figure 34), because of the high temperature developed during the exothermic curing reaction. This influence is particularly evident for fast curing adhesives or in large bead applications, for example in the cases of gap filling or in wind turbine blade bonding.

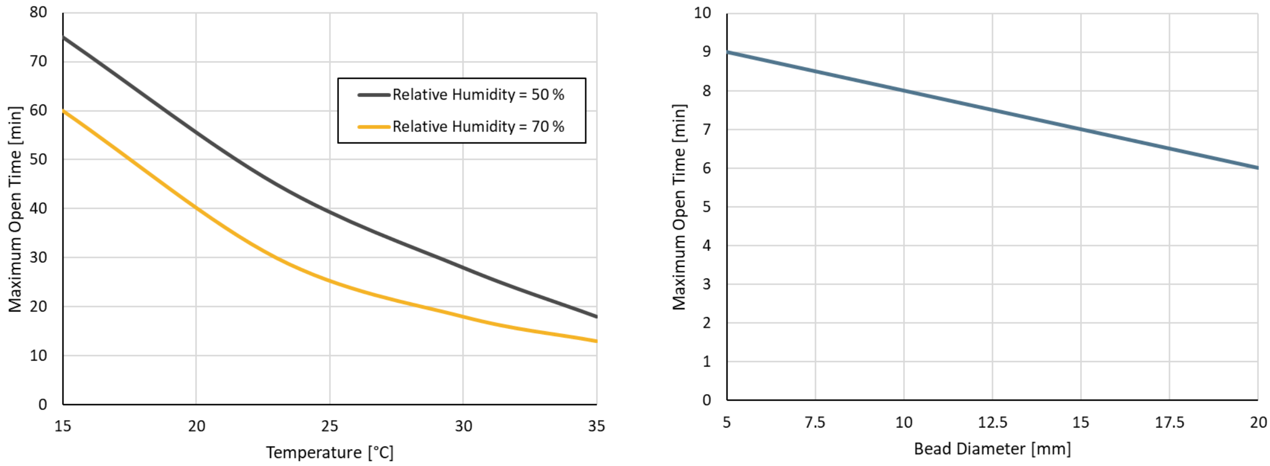


Figure 34 *Exemplary open time dependency on humidity (for a slow curing polyurethane) and bead size (for a fast curing polyurethane).*

IMPORTANT NOTE

To minimize formation of thermal stresses in the bonded joints, the substrate temperature shall not be outside the application temperature range of more than ±5 °C. A good practice consists in climatizing both adhesive and substrates at optimal application conditions for about 2 hours prior to bonding.

Generally, the surface preparation shall also occur no longer than 2 hours before adhesive application. This is particularly relevant in the case of metal grinding; for instance, new oxide layers grow very fast at room temperature on grinded aluminum surfaces. Since substrate quality is equally important as adhesive features for the bonding success, it is recommended to implement traceability measures and quality control of incoming substrates. Constant substrate surfaces should be ensured by means of agreements with the suppliers and any change in the substrate quality must be communicated, because it may affect the bonding.

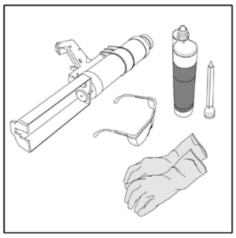
4.2.1 APPLICATION INSTRUCTIONS

Application of structural adhesives out of bulk packaging is carried out by apposite pumping, mixing and dispensing equipment (Figure 35). A variety of machines are available in the market or can be ad hoc assembled for special production and automation needs. Sika offers support for selecting and installing suitable and cost-effective equipment thanks to specialized system engineers.

Structural adhesives are also frequently applied out of cartridges in industrial environment, both for prototyping and for large scale production. In this context, attention must be paid for 2C adhesive systems, which require mixing precision during the application. For several adhesives, deviations from the correct mixing ratio of more than 10 % are normally not acceptable.

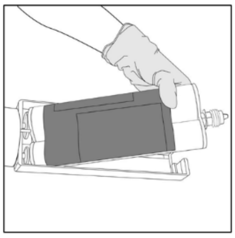
Figure 35 *Dispensing equipment for two-component adhesives out of pails (left) and drums (right).*

Most 2C adhesives are packed in coaxial cartridges, externally similar to 1C cartridges, or in dual cartridges (i.e., side-by-side cartridges). For both coaxial and dual cartridges, two types of dispensing systems – also called "application guns" – are available: (1) manual and (2) automatic dispensers; these latter can be electrically or pneumatically driven. Manual dispensers are not recommended for 2C adhesives, because they cannot ensure a constant and correct mixing outflow due to trigger push-release effects. On the other side, automatic dispensers are only indicated if having pistons and driving rods; dispensers without moving rods must not be used, because they may blow air inside the cartridges. Moreover, it is suggested to keep a constant speed when applying the adhesive and not to work with dispensers at their maximum settings (force or pressure) due to instability reasons and possible damages to cartridges.

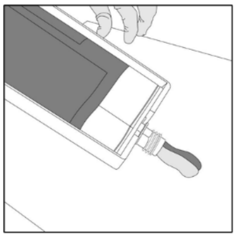


Equipment required

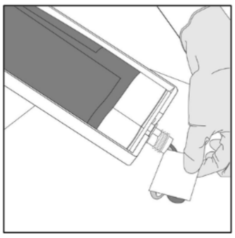
1. Unscrew plastic retaining nut and pull out blanking plug



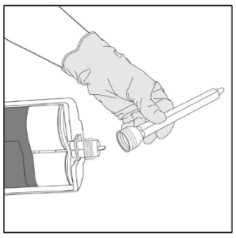
2. Place cartridge into dispenser and ensure it is engaged correctly



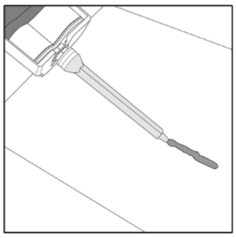
3. Extrude 5-10 mm of components to equalize filling levels and avoid air entrapment



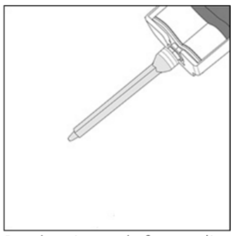
4. Clean outlet to avoid contamination of mixing nozzle



5. Mount static mixer and tighten it with retaining nut



6. Extrude a bead of same length as the static mixer to ensure homogeneous mixing



7. Product is ready for application on substrates (after surface preparation)

Figure 36 *Instruction for application of 2C adhesives out of cartridges.*

Figure 36 illustrates the basic steps to apply 2C adhesives out of cartridges. It is important to extrude the two components before mounting the mixer, since their filling levels may not be the equal. Prior to application on the substrates, it is as well necessary to extrude and dispose an adhesive bead of at least the same length of the mixer, in order to obtain a homogeneously mixed material. A useful quality check, when the two components have different colors, is to perform a "butterfly" test, which consists in applying a bead on a paper and folding it. By re-opening the paper, it is possible visually ensure the color of the extruded material is uniform (Figure 37). A further quality check – the "curing bead" test – can be carried out by leaving an extra adhesive bead curing in the same environment of the bonded joint. When fully cured, this bead gives a practical indication that the adhesive in the joint is cured as well. If the bead does not cure in due time, it will represent a sign of possible mixing mistakes and a need for further checks or corrective measures (e.g., a post-curing stage, mounting local mechanical fixations, etc.).

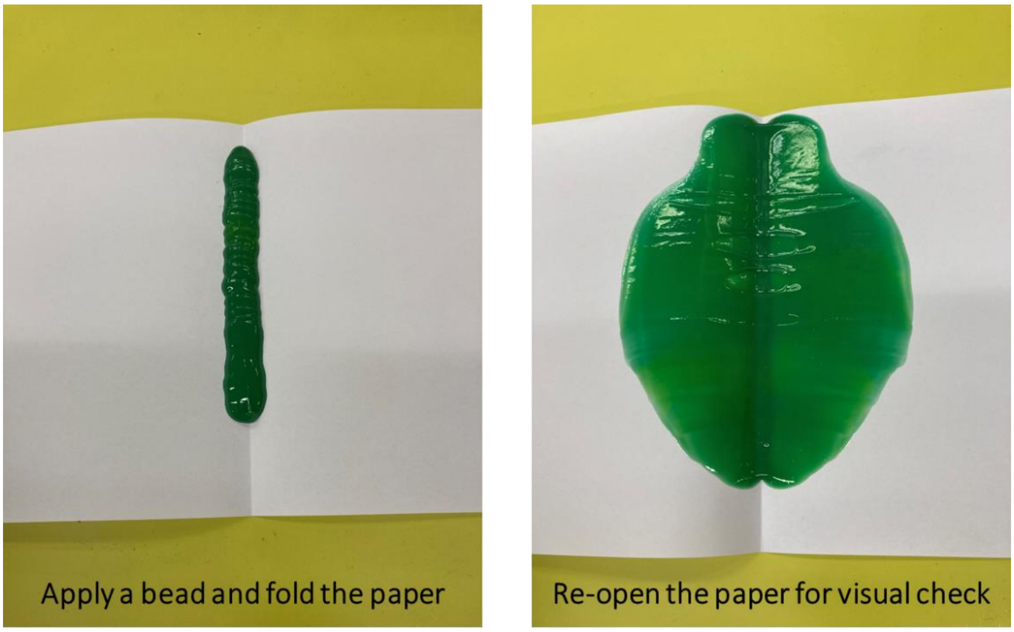


Figure 37 *Butterfly test.*

4.3 ADHESIVE CHOICE FOR STRUCTURAL BONDING

Selecting a suitable adhesive for a given structural bonding application is a complex task. The complexity of the adhesive choice goes hand in hand with the quality of the specification requirements. When too generic or little information on the application is available, several adhesives can meet the requirements and it is hard to narrow down the list of best candidates for field tests. On the other side, over-specifying the requirements should be avoided, because it may exclude many solutions that can fulfill the real application needs. The "ideal" adhesive – with the fastest curing, highest strength, largest flexibility, greatest aging resistance, etc. – either does not exist or it is too expensive and over-engineered for most applications. Another flawed approach to adhesive selection is often followed when seeking an alternative product for an existing application: in this case, it can be misleading to base the specifications on the current adhesive datasheet values, rather than the actual application requirements.

This document has already explicated that several factors concur to the success of a bonded joint. Here, it is worth recapping the key aspects to consider for outlining specification requirements and guiding the adhesive choice:

- Adherend types and surfaces. A good match between the characteristics of the adhesives and those of the substrates (types, stiffness, surface treatments, etc.) is essential for all bonding applications and, as already seen, some combinations – like rigid adhesives and flexible adherends – are generally not recommended.
- Performance and functionality of the joints. The specifiers and designers need to clearly define the engineering and operative requirements: types and magnitude of external loads, frequency of the applied

forces (e.g., constant forces, vibrations, cyclic loads, one-time impact or crash, etc.), regular service temperatures and occasional peak temperatures, environmental conditions, needs for gap filling or compensating thermal stresses between dissimilar materials, aesthetic requirements and so on. In this regard, different stress conditions are expected if the adhesives are used alone or in combination with mechanical fixations (hybrid joints).

- Lifetime service conditions. Connected to the above point, adhesive specifications and selection must contemplate the whole service life of the joints. Opportune qualification criteria should be set for the long-term effects of mechanical loads and environmental aging. Of course, the requirements will differ depending on, for example, outdoor or indoor applications, exposed or sealed/coated joints, dry or humid/underwater conditions, continuous or occasional exposure to cleaning agents, corrosive environments, aggressive chemicals or any particular fluids like oils, fuels, acid solutions, etc.
- Assembly process conditions. Besides the end use performance, the adhesive features should fit the manufacturing constraints or, vice versa, the assembly shall be built around the bonding process. In this context, the requirements focus on the application properties of the adhesive materials (i.e., viscosity, sagging behavior, open and handling times, curing characteristics, etc.) at the production conditions (temperature and humidity above all others). Specific equipment for adhesive dispensing, mixing, curing and post-curing (like ovens or lamps), as well as for tooling and finishing operations, must be regarded, together with the needs for trained/experienced applicators and adequate spaces for conditioned storage and application.
- Repair and end-of-life aspects. Depending on the final application, it may be necessary to define prerequisites and solutions for maintenance or repair in the case of damage. Moreover, since bonded joints are normally not designed for easy opening and disassembly, it may be relevant to account for sustainability and end-of-life aspects (recyclability, reuse, disposal, etc.).

As many contrasting requirements may be included in the specification set, it is reasonable to fix priorities and distinguish between musts and wishes. Finally, the adhesive choice is simplified by following a funnel principle, consisting in sequential selection rounds, and must be always finalized by real tests and validation in the field.

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