GENERAL GUIDELINE
STRUCTURAL BODY-IN-WHITE BONDING

VEHICLE BODY BONDING WITH 1-COMPONENT SikaPower® ADHESIVES

April 2023

BUILDING TRUST

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1 PREFACE

This general guide contains information and recommendations concerning one-component, hot curing adhesives and related materials, adherends, processes and equipment. Its scope is structural applications, typically in combination with spot joints (resistance spot welds, self-piercing rivets). Adhesives applied in the body shop for other purposes, such as sealing, anti-flutter, hemming, are not the object of the present guideline.

This document shall provide basic and easy-to-access information for unexperienced companies and personnel along the process, from material and design & development engineers to shop floor and quality personnel. 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.

For more detailed information related to applications or products mentioned in this document, contact Sika Automotive. A broader general guideline about structural bonding with various hot and cold curing (two-component) adhesive types is issued by Sika Services AG and can be procured from Sika. Guidelines about elastic bonding and sealing are available as well.

This information as well as our other advisory services are given in good faith and based on our current knowledge and experience in the correct application of our products. It does, however, not relieve the user of the product from testing the product's suitability for the intended application and purpose under the actual conditions.

In practice, the differences in materials, substrates, and actual site conditions are such that no warranty in respect of merchantability or of fitness for a particular purpose, nor any liability arising out of any legal relationship whatsoever, can be inferred either from this information, or from any written recommendations, or from any other advice offered. It is the customer's responsibility to maintain consistent conditions of materials, substrates and actual site conditions as well as standards of workmanship.

The customer is solely responsible for the use and processing of our products as well as compliance with our technical advice. Consult the Product Data Sheet prior to any use and processing. The proprietary rights of third parties must be observed. Our most current General Sales Conditions shall apply. Except as expressly agreed in writing, Sika's warranty is governed exclusively by our General Sales Conditions.

2 TERMS AND ABBREVIATIONS

BIW	Body in White: car body assembled in the body shop and undergoing the e-coating (electrodeposition coating) process with passage of electrocoat bath and rinse stations, curing oven and subsequent ovens
CAD	Computer Aided Design
CAE	Computer Aided Engineering (mostly with the Finite Element Method)
FEM	Finite Element Methods
OEM	Original Equipment Manufacturer, Car Manufacturer
NVH	Noise, Vibration, Harshness
RSW	Resistance Spot Weld
SPR	Self Piercing Rivet
SLJ	Single Lap Joint
Hybrid bonding or joining	bonding in combination with other joining technique
Rivbonding	bonding in combination with rivets / self-piercing rivets
Weldbonding	bonding in combination with spot welds / resistance spot welds

3 INTRODUCTION

3.1 HISTORICAL DEVELOPMENT AND OEM INTRODUCTION, BENEFITS OF BONDING

3.1.1 SPOT JOINING

Structural body joints, typically profile flanges and overlap joints, are traditionally connected with spot welds or – in the case of aluminum or mixed steel–aluminum bodies, – with rivets. Both spot joining technologies are long established, fast and in many cases cost efficient ways to connect body panels and other metal parts such as castings or extruded profiles. The punctual attachment with unconnected areas in-between the spot joints leads to inferior stiffness compared with continuously connected parts, both in service conditions (with respect to NVH / body rigidity, and locally, e.g., in hinge areas) and in nodal and sectional resistance against deformations when subjected to crash deformation. In addition, the local load introduction leads to poor durability. In crash loads, the joint strength is limited and the heat introduction by welding alters (mostly weakens) the base material in the heat affected zone. The punching of the panels with rivets also locally weakens the components. The number of spot joints cannot arbitrarily be increased as a measure to increase joint strength; when the pitch falls below a certain limit the opposite effect will occur. Also, increasing the spot welds leads to higher thermal input and to more severe distortion of the body.

3.1.2 MECHANICAL, CORROSION AND MANUFACTURING BENEFITS

Adhesive bonding provides a continuous connection of a certain width, thus compensating for the shortcomings mentioned above and bringing additional stiffness, strength, and toughness to a joint. Consequently, bonding improves local and global stiffness, strength, crash, and durability behavior.

Figure 1 displays crushed double hat profiles in a drop tower, with flanges joined with different techniques. Spotwelded profile length is reduced from 500 mm to 270 mm, bonded and weldbonded profile length is reduced from 500 mm to 310 mm – 340 mm length. Energy uptake in a drop tower test is identical; higher force level during compression from increased resistance against deformation in bonded and weldbonded profile leads to less shortening.

Figure 1: Spotwelded, bonded and weldbonded double hat profiles after crushing in a drop tower

In the welded profile, the flanges separate and don't deform in parallel, leading to lower deformation resistance, see **Figure 2**.

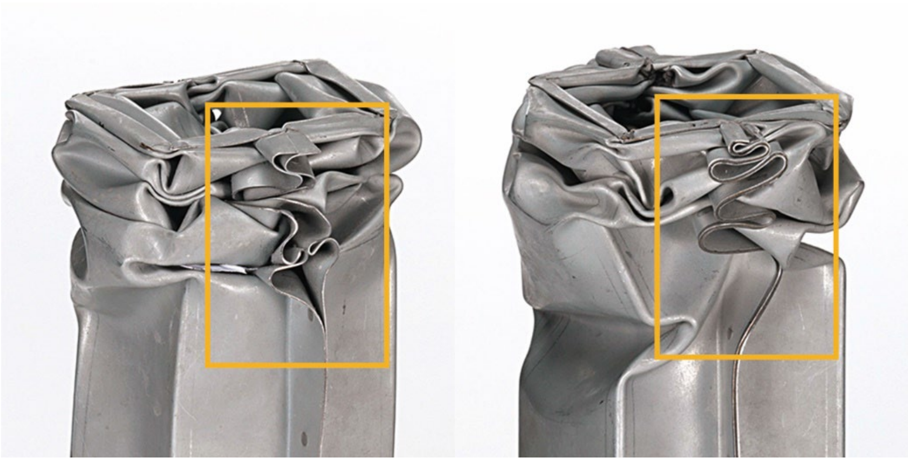


Figure 2: Detailed spotwelded and weldbonded profile

Other benefits, namely corrosion protection and sealing, are more than just positive side effects and form independent arguments in favor of bonding.

Also, manufacturing issues with spot welding and riveting can be overcome with adhesives: two-sided joint accessibility of the assembled parts for weld gun and rivet setter must be given, without interferences with adherends, (e.g., in narrow flanges or deep sections) – with bonding, no flange accessibility is needed after assembling the adherends. Also, no contact is needed between the joined adherends; consequently tolerances, also of larger size with sub-assembly joining, and gaps of up to several millimeters thickness can be bridged. In such applications care has to be taken to avoid kissing bonds (see 5.1.1 and 9.3).

3.1.3 INTRODUCTION OF ADHESIVE BODY BONDING AT THE CAR MANUFACTURERS

These positive effects were already seen decades ago, and the impact on the process and the body shop floor to use adhesive application is low since the curing takes place in the e-coat oven and does not require a change or additional process steps, apart from the adhesive application itself. First components, such as closures, were weldbonded, proving process and service feasibility and longevity over the years. In parallel the body adhesives were improved with respect to various aspects such as shelf-life stability, lubricant absorption, corrosion protection, wash-out stability, baking condition robustness, and toughness.

3.1.4 LIGHTWEIGHTING

The positive impact on body stiffness and fatigue strength became important with the introduction of high and ultra-high strength steel; these grades allowed for weight reduction by using thinner sheets with equal crash performance. The concomitant loss of body rigidity in service is compensated with bonding; body profiles and nodes are stiffened considerably when flanges and overlap joints are attached continuously and rigidly. Also, the connected sheet regions, forming a "sandwich" when bonded, clearly show less deformation, especially at the load introduction at spot joints, and therewith are much less sensitive to fatigue failure.

With the trend of reducing body weight, aluminum was introduced and with its lower Young's modulus compared to steel, body stiffness needed to be enhanced – it is obvious, that aluminum intense car bodies contain a higher amount of adhesive.

The joining of new, high strength and mixed material panels is a challenge with many aspects, and solutions must be designed for the specific joints. The amount and variety of applied mechanical fasteners consequently increased in the past years, and complexity of manufacturing processes raised dramatically. Bonding features a versatile joining method and helps to reduce complexity in the shop floor.

For these reasons bonding is an important enabler of light-weighting.

3.2 TODAY'S USAGE OF STRUCTURAL BODY ADHESIVES

Finally, in the first decade of the century the way to industrial and large-scale use of body adhesive was paved and many OEMs are benefiting from its various advantages. Today most car bodies contain structural or crash toughened adhesives, with bond lengths ranging from 30 to 200 meters and more. This corresponds to a weight of 0.2 kg (30 m) and 1.5 kg (200 m). An application example is given in **Figure 3**.

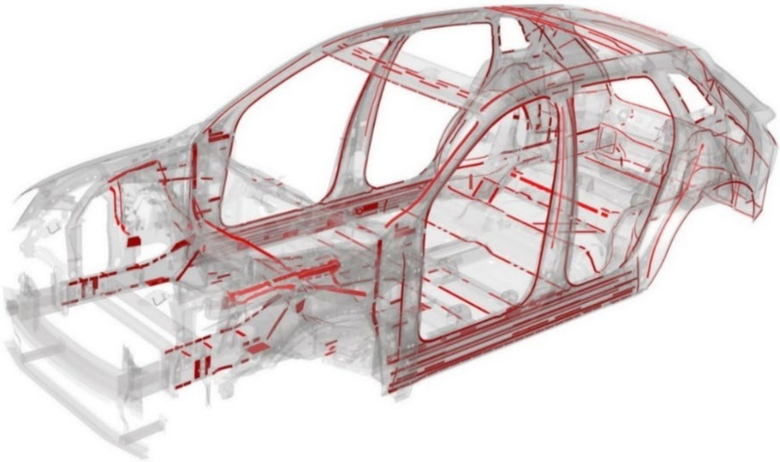


Figure 3: Structural adhesive applications in Audi e-tron with aluminum top hat; Courtesy of Novelis

MAIN ADVANTAGES OF USING ADHESIVE BONDS IN BIW:

- Improving structural performance
- Saving weight
- Improving corrosion protection
- Isolation against galvanic corrosion in mixed-material joints

4 MATERIALS AND SURFACES

To reach a high and robust joint strength, the adhesion strength (interfacial strength between adhesive and adherend) must be superior to the cohesive strength (strength inside the adhesive). This is verified on simple specimen types (commonly lap shear) By evaluating the fracture surface, after fracture, the remaining adhesive on the adherend surfaces must be detectable. The classification of fracture surfaces is regulated in standard DIN EN ISO 10365 and DVS 3302. Typical fracture profiles are given in **Table 1**. In addition, a so-called white failure is also accepted with body bonding, where one adherend seems to be blank but the fracture surface on the adhesive is whitish and force level is high. With adequate material combinations and surface pretreatments, the adhesion strength can be adjusted if necessary.

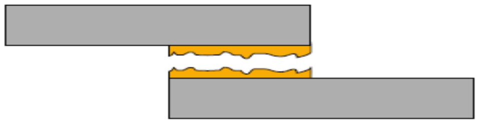
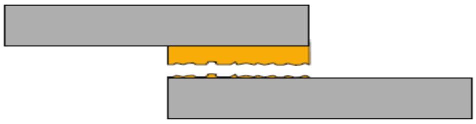
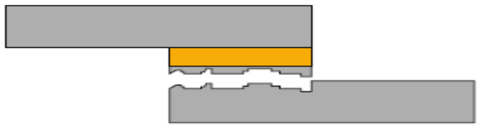
Failure location	Designation	Schematic	Note
Within the adhesive layer	Cohesive Failure (CF)		Both adherends show an adhesive layer
	Surface-close Cohesive Failure (SCF)		A thin layer of adhesive lays on one adherend
	White Failure (WF)		High force transfer cause stress whitening damage of the adhesive
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)

Table 1: Failure mode designations

In general, compatibility is a given with commonly used adherend materials, lubricants and adhesives. Nevertheless, with any new material and application release the OEMs request extensive testing to verify adhesion, corrosion resistance and ageing (long term behavior).

4.1 ADHERENDS

4.1.1 STEEL

The most common adherends are deep-drawn steels of various grades. They are handled as coils with lubricants for corrosion protection and drawability. In the nominal amount of evenly distributed 2-3 g/m^2, these oils, greases or hotmelts will thermally diffuse into the adhesive during heat curing and get absorbed. The adhesion is not negatively affected.

For the fabrication of component or coupon specimens it must be ensured that no accumulations of lubricants occur, e.g., from upright storage in racks.

On degreased and cleaned steel surfaces with good practice procedure and working materials, a high adhesion strength is achieved.

Steels with coating (e.g., galvanized steel or AlSi on boron steel) must be investigated with care since some coatings tend to delaminate and can't transfer high loads or resist large stress peaks with stiff adhesives. The same care must be taken when bonding on e-coat, even though the adhesion strength of e-coat on the adherend is usually high, this being the same case with paints. The use of more flexible adhesives can be effective to reach a cohesive failure rather than a coating delamination.

Adhesion and corrosion resistance on stainless steel needs to be verified.

4.1.2 ALUMINUM

Aluminum parts are used in various forms and alloys (5xxx, 6xxx, 7xxx) in car bodies: as deep-drawn panels, high pressure die castings and extrusion profiles. For castings the use of any release agents in the mold must be considered since they have a great impact on adhesion.

For all aluminum parts a surface treatment is required to remove or stabilize the oxide layer – without a proper pretreatment the corrosion performance is not given. Titanium / Zirconium passivation, Silane based treatments, anodizing, organic treatments, pickling, and laser treatment are the most common options.

Complete flange coverage with adhesive is required to protect the substrates from corrosion. If the contact areas are not wetted with e-coat and humidity is trapped in thin joints, it often leads to harsh conditions favoring corrosion.

4.1.3 OTHERS

In some vehicle bodies fiber reinforced plastics are used. Generally, epoxy-based body adhesives show a good adhesion on thermosets and many heat-resistant thermoplastics, with use of a suitable surface pretreatment and controlled surface conditions. With laminated composites the topic of layer delamination must be considered, analogous to above mentioned coatings on steel. Since they are niche applications bonding plastic components is not discussed further.

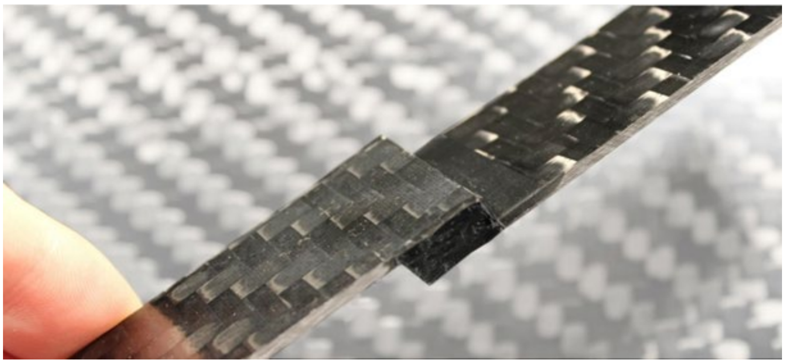


Figure 4: Bonding of carbon fiber reinforced plastic composite

4.1.4 MIXED MATERIALS

In mixed metal joints special attention must be given to the galvanic corrosion: metals with different electrochemical potential, and electrically conductive materials as carbon fibers, lead to this special form of contact corrosion. Adhesives are well suited to provide an isolating function, and along with a flawless e-coating galvanic corrosion can be prevented.

Another sensitive topic is the so-called delta-alpha management: parts with different coefficients of thermal expansion will exhibit relative deformations between the adherend partners, leading to stretching and stresses in the adhesive, in some cases even to failure during cooling in the e-coating process. See also 6.2, 8.2 and 9.

It is crucial to ensure good adhesion strength between adherend and adhesive. The material of the bonded parts and their surface condition play an important role. Pretreatment measures improve the adhesion.

In mixed material joints the galvanic corrosion can be prevented with the isolating effect of adhesives. The difference in coefficient of thermal elongation can lead to high stresses in the bond line during cooling in the e-coating process.

4.2 ADHESIVES

The brand name of Sika's epoxy adhesives is SikaPower®. Under this name, established one-component heat curing body adhesives as well as two-component, cold curing epoxy materials have a long history in industrial applications. New and improved material grades are constantly in development.

The adhesive described in the following can have different viscosity for warm or cold pumping; see chapter 8.

4.2.1 STRUCTURAL ADHESIVES

Adhesives developed and used to stiffen and reinforce car bodies are so-called structural adhesives. They can transfer high loads but often exhibit a brittle failure; therefore, these adhesives only offer limited benefit to prevent failure in highly loaded joints in crash cases.

4.2.2 TOUGHENED ADHESIVES

To overcome the drawbacks of structural adhesives, a toughening mechanism was developed: soft polymer domains in the brittle epoxy matrix that stop or redirect a crack. Additional energy is then needed to restart cracking.

Crash toughened adhesives are characterized by a high peel resistance. This resistance would also become visible in a destructive shear test with a propagating crack, but this is difficult to perform experimentally. For crash application a special focus is laid on the impact peel resistance – a value characterizing the toughness at high loading rates, to exclude embrittlement compared to low rates, measured with the efficient and easy to perform dynamic impact peel / wedge impact test, see **Figure 5**. This impact peel value and the term "toughness" means that a high amount of energy is needed to drive a crack through a joint.

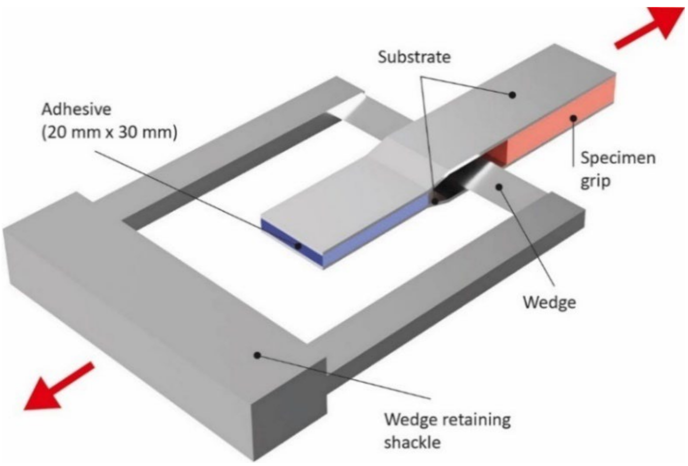


Figure 5: Impact peel test: sample and shackle with wedge (shackle is moved by a pendulum when it reached the lowest position)

4.2.3 MULTI-MATERIAL BONDING ADHESIVES

MBX adhesives (Multi Material Bonding Excellence) are designed for mixed material bonding, especially for metal–plastic combinations. These types of adhesives can better accommodate the stress created during curing, resulting from different coefficients of thermal expansion of the two adherents. This type of adhesives can also offer benefits when delamination is a problem (see 4.1.3.).

4.2.4 LOW BAKE ADHESIVES

Low bake adhesives can be cured at lower temperature than standard materials, see **Figure 6**. There are two main reasons of why such adhesives are used:

a) In metal intensive structures like the battery frame of electro vehicles the targeted temperature is not achieved.

b) To save energy and to reduce CO2 emissions, the temperature of the electro coat oven is reduced.

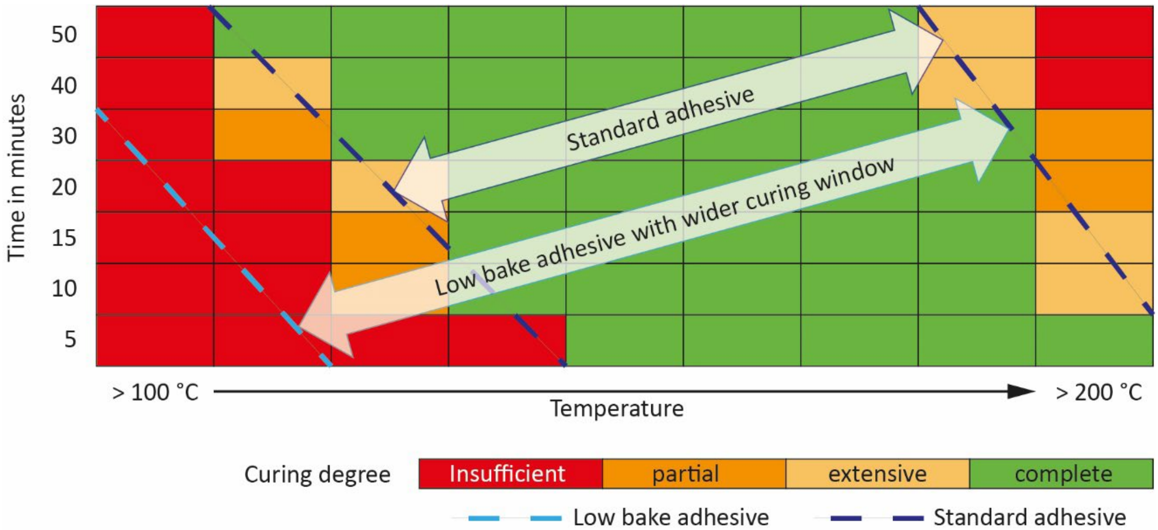


Figure 6: Curing window of standard and low bake adhesives

4.2.5 ADHESIVES CONTAINING GLASS BEADS

Materials with glass spheres (2 % in weight, 0.15 – 0.25 mm diameter, without affecting the mechanical properties) are commonly used in hem-flange applications to limit adhesive being squeezed out of the joint, ensuring a more homogeneous adhesive distribution, and reducing metal spring back, to ensure a good sealing function. With high forces the spheres can be crushed, or they can penetrate the adherends to a certain extent – in hemming this results in a positive effect of flanges latching on to each other and increasing the dimensional stability after forming. Such materials are increasingly used in structural applications besides hemming to limit the minimum gap size and squeeze out at spot joints. Weldbonding with glass filled adhesives is generally possible but it needs to be checked if the welding parameters are to be adapted.

THE GROUP OF STRUCTURAL BODY ADHESIVES CAN BE DIVIDED INTO THESE SUBGROUPS:

- Plain structural adhesives: used for stiffness improvement
- Semi-crash resistant adhesives: structural adhesives with medium crash toughness
- Crash-resistant adhesives: structural adhesives with high crash toughness
- MBX adhesives: structural adhesives designed for mixed material bonding
- Low Bake adhesives: structural adhesives which can be cured at lower temperatures

The adhesives can be supplied with glass beads for gap control and squeezing limitation.

The adhesives can have different viscosities for cold or warm pumping.

5 MECHANICAL BEHAVIOUR AND TESTING

Testing of adhesives and bonded joints is described extensively in the literature and standards. Some examples of frequently used standards are given in **Table 2**.

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
Compression	ISO 604, ASTM D 695	Compression Strength
Fracture toughness	ISO 13586, ASTM D 3433	Critical energy release rate (mode I) G_{Ic} Critical stress intensity factor (mode I) K_{Ic}

Table 2: Main mechanical tests for structural adhesives

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

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	DIN EN 17408	Viscosity at 45°C

Table 3: Main tests for thermal and rheological adhesive characterization; * DMA = Dynamic Mechanical Analysis to determine the glass transition temperature

Figure 7 displays a single lap joint shear test and the resulting technical stress-strain curve:

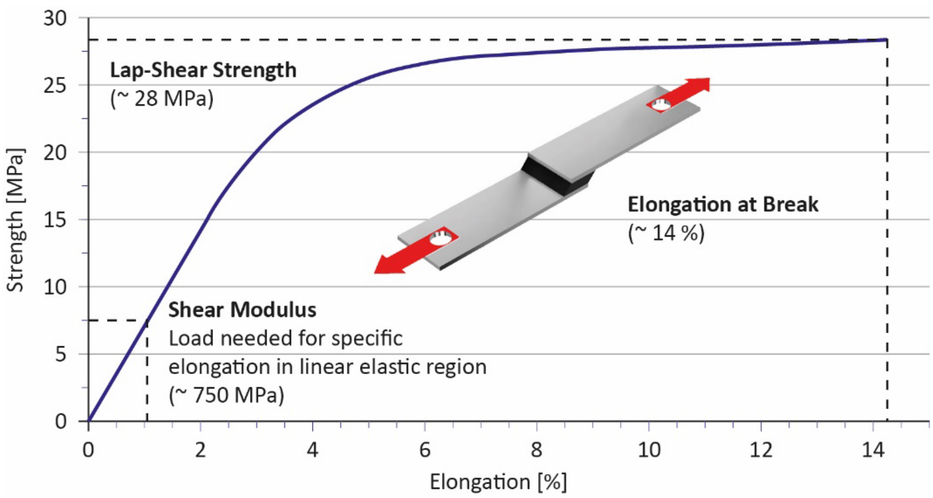


Figure 7: Illustration of single lap joint specimen and results

OEMs have their own specifications and methods to compare different materials and to evaluate if their requirements are met. This chapter focuses on single tests, results and their interpretation, impact of certain parameters and sensitivities to generate a basic understanding of mechanisms in a bonded joint.

In the following sections, good adhesion on the substrates and cohesive fracture in the adhesive is assumed.

5.1 COUPON TESTS FOR JOINT CHARACTERISATION

Most frequently used specimen types are the single lap joint and the T-peel specimen. These tests represent typical applications and characterize the system of joined parts, rather than the adhesive itself. The substrates (material, material grade, thickness) affect the results. They serve for comparative studies, fracture surface evaluation (adhesive/cohesive, see **Table 1**), aging and corrosion investigations.

Care must be taken when talking about "strength" results from such tests; the terms "normalized force" (force per area) or "nominal stress / strength" or "technical stress / strength" are more precise, as discussed in the following. Also, the "displacement" designation needs a cautious consideration; in most cases displacement is read from crosshead displacement (test machine output), containing machine compliance and adherend lengthening, and therefore is not representative for, but exceeding, the "adhesive elongation" or "tensile / shear strain".

Despite the shortcomings these samples provide benefits because purchasing of thin metal panels is feasible for a supplier company. Purchasing massive steel blocks for pure adhesive material testing is more difficult and costly, produces more waste or must be cleaned for reusing, and high precision in sample preparation and mounting in test devices to avoid any pre-stresses is needed.

5.1.1 BONDED SPECIMENS

In the following, the specimens and results of single lap joint and T-peel tests are presented and discussed.

From the test machine or additional sensors and measuring feeders, the force and displacement signals are recorded. The force is typically divided by the bonded area to derive the system's "strength" which should not be interpreted as the adhesive's fracture strength since it does not represent the stress at failure in the adhesive. The real stress distribution, represented in **Figure 9**, is non-homogeneous. The thin substrates show more pronounced bending meaning the peel stress at the ends of the overlap is causing failure, rather than the shear stress (see. **Figure 8**). Also, with higher adhesive thickness the bending moment increases, leading to higher stress peaks and consequently lower transferable force, as shown in **Diagram 1**.

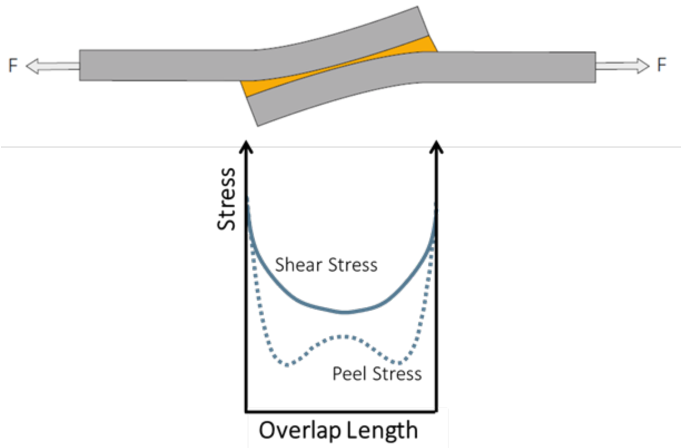


Figure 8: Bending and stress peaks in SLJ (analytical solution)

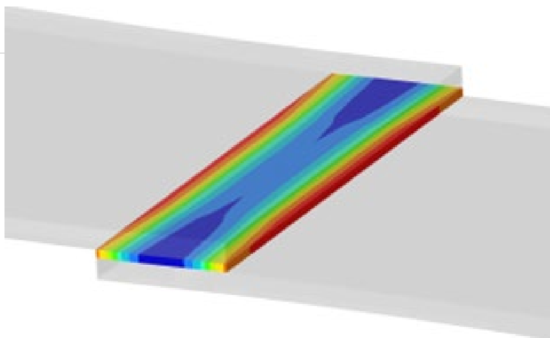


Figure 9: FEM result von-Mises stress in SLJ (red = high stress, blue low stress)

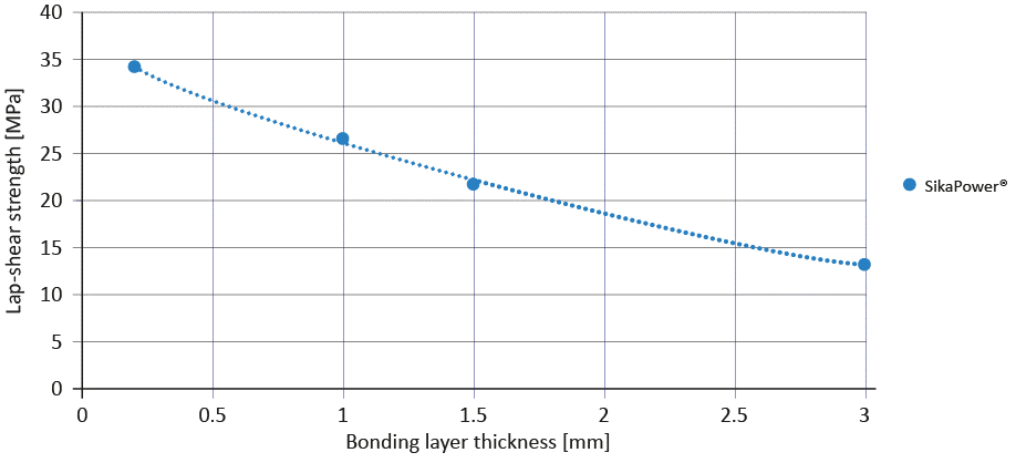


Diagram 1: Technical lap shear strength vs. adhesive thickness (high strength steel HC680 +ZE75/75 1.0 mm thickness)

It must be clearly noted that this apparent loss in technical lap shear strength with increasing bond line thickness should by no means exclude bonding to join parts with thicker gaps. Due to the continuous, two-dimensional connection, the strength and also the joint stiffness are still on a high level, compared to spot joints. As countermeasure against this loss, an increase of flange width or overlap length can serve to some extent. When a certain width or length is reached, a further increase does not affect the failure force since – especially with stiff body adhesives – the local stress peaks causing the failure are no more reduced. With higher bond line thickness there is also a positive effect: the so-called toughness - energy which must be applied to drive a crack through the joint - does greatly increase with thicker bond lines.

The T-peel test (**Figure 10**) is frequently used to demonstrate the toughness. It is mostly performed at low test velocity. The displacement is not meaningful for the adhesive lengthening since it contains stretching of the substrates. The force curve in **Diagram 2** is analyzed to judge the stability of crack propagation and – in the stable (= plateau) region – about the resistance against peeling. The adhesive filling grade in the radius / fillet drives the first force peak; this peak force is not evaluated.

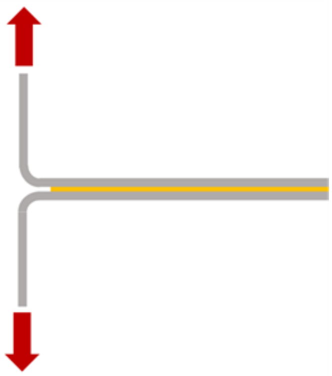


Figure 10: Illustration of T-peel test specimen

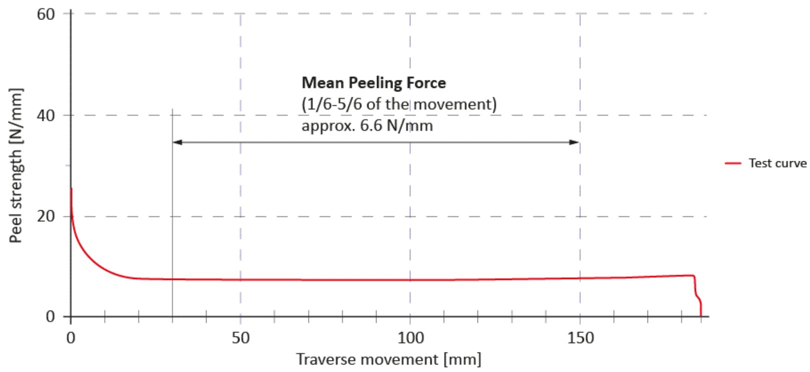


Diagram 2: T-peel test results

To prove the toughness at high speed, the impact peel or wedge impact test is utilized (see 4.2.2).

5.1.2 HYBRID JOINED SPECIMENS

Since most flange and overlap joints in vehicle bodies use adhesive in combination with spot joints, the performance increase with bonding in spot joints is explained.

The following diagrams originate from two research projects with test results created by Laboratory for Material and Joining Technology (LWF) Paderborn. They show force-displacement curves of spot joined (red), bonded (black), and hybrid joined (blue) specimens. Different steel types were used on the two slides, so curves of bonded samples are not directly comparable. Unlike the T-peel test discussed above, the peel test is performed on thicker, higher strength steel substrates, and the parallel part is shorter; consequently, no force plateau is formed.

In **Diagram 3** and **Diagram 4** results with spot welds are presented from static and fatigue tests. Strength of the bonded and hybrid joined specimens are higher than with the spotwelded only joints, whereas the spotwelded joints show a higher deformation at failure. The curve of the hybrid joined specimen represents the envelope of both single joining methods. The Wöhler curve of fatigue strength is clearly higher and shows a smaller slope with adhesive bonding. No apparent difference between adhesive bonding and hybrid joining is visible.

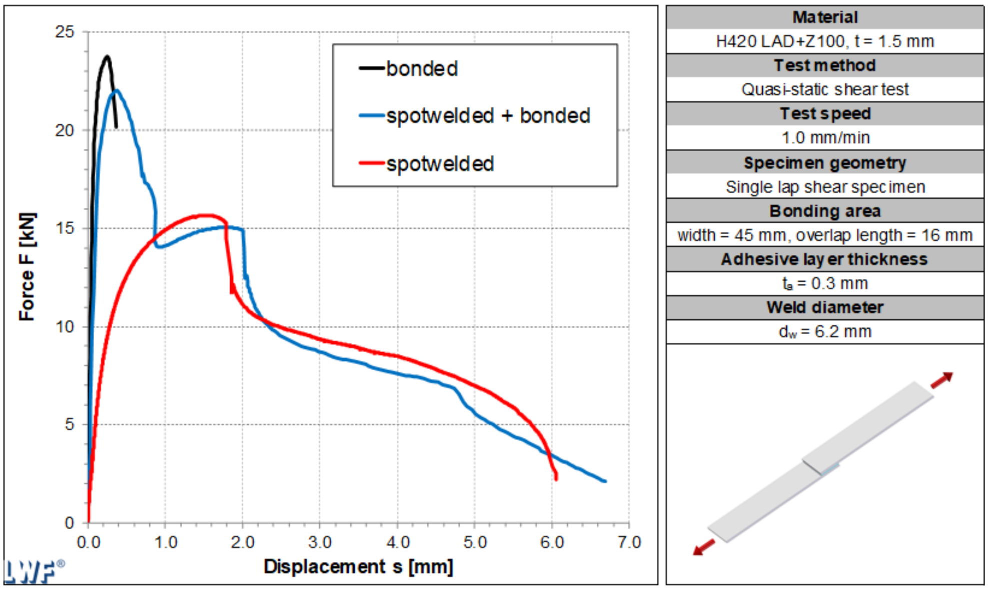


Diagram 3: Quasi-static lap shear test; courtesy of LWF (Laboratorium für Werkstoff- und Fügetechnik), Universität Paderborn; Source: FOSTA P958, Forschungsvereinigung Stahlanwendung e. V.

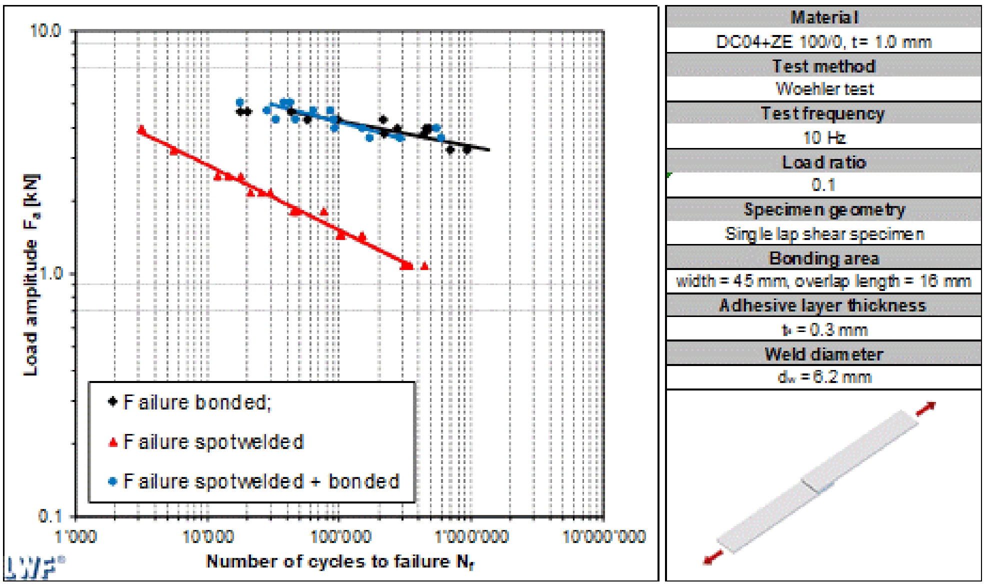
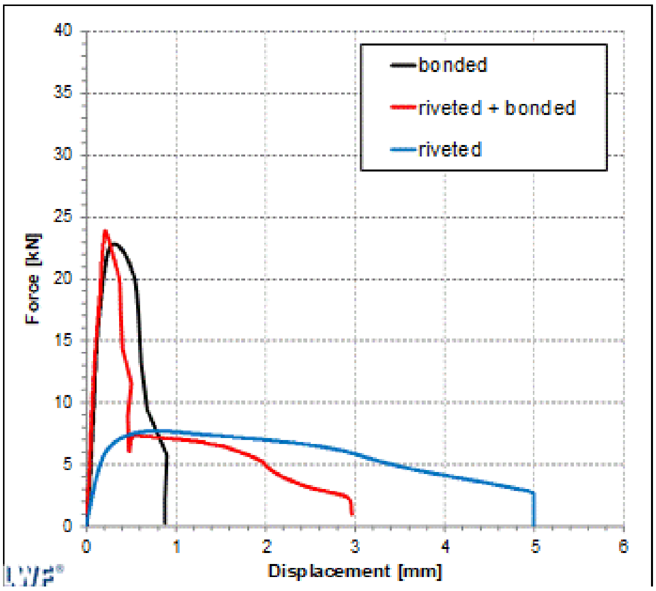


Diagram 4: Cyclic lap shear test until failure; courtesy of LWF (Laboratorium für Werkstoff- und Fügetechnik), Universität Paderborn; Source: FOSTA P958, Forschungsvereinigung Stahlanwendung e. V.

In **Diagram 5** and **Diagram 6** results with rivets are represented from static and high-speed test. The findings are similar: the hybrid joined curve represents the envelope of both single joining methods, and strength with bonded specimens is clearly higher which becomes even more pronounced at the high-test speed due to the viscous behavior of the polymer.



Material
H340LAD+Z100, t = 1.5 mm
Test speed
10 mm/min
Specimen geometry
Single lap shear specimen
Bonding area
width = 45 mm, overlap length = 16 mm
Adhesive layer thickness
t_a = 0.3 mm
Rivet
C 5x5 SKR H4

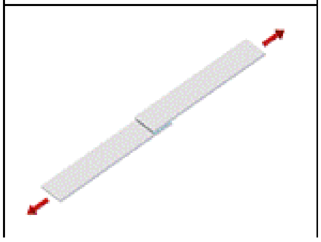
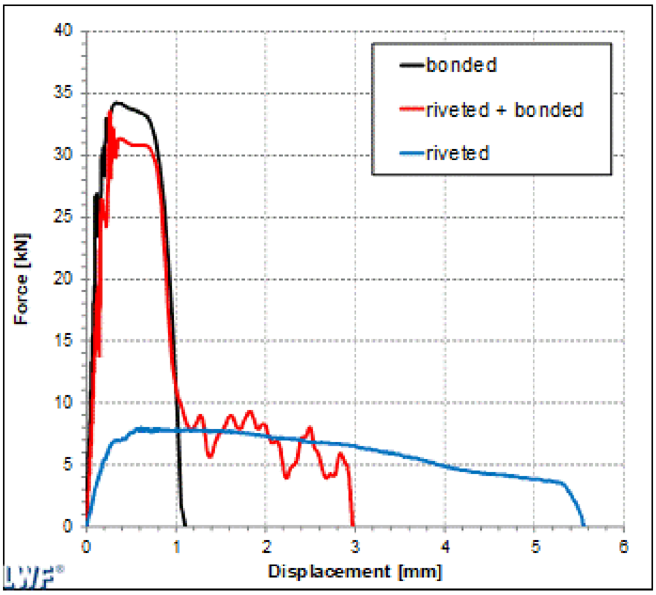


Diagram 5: Quasi-static lap shear test; courtesy of LWF (Laboratorium für Werkstoff- und Fügetechnik), Universität Paderborn; Source: FOSTA P795, Forschungsvereinigung Stahlanwendung e. V.



Material
H340LAD+Z100, t = 1.5 mm
Test speed
1.5 m/s
Specimen geometry
Single lap shear specimen
Bonding area
width = 45 mm, overlap length = 16 mm
Adhesive layer thickness
t_a = 0.3 mm
Rivet
C 5x5 SKR H4

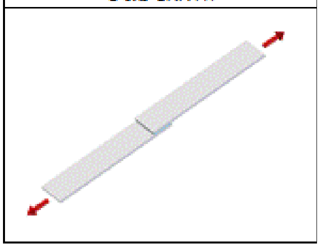


Diagram 6: High speed lap shear test; courtesy of LWF (Laboratorium für Werkstoff- und Fügetechnik), Universität Paderborn; Source: FOSTA P795, Forschungsvereinigung Stahlanwendung e. V.

All findings are applicable also to peel specimens (not shown here).

Bonding in addition to spot joining multiplies the stiffness and the maximum force whereas the spot joint provides a large deformation at final separation of the adherends. The force-displacement curve of a hybrid joined specimen corresponds to the envelope of the force-displacement curves of the single joining techniques.

5.2 MATERIAL TESTS

Tests to evaluate the adhesive itself – without substrate influence – and to characterize CAE material card parameters are briefly described in this chapter.

5.2.1 BULK TEST

A basic test is the tensile test on dumbbell samples, see Diagram 7. It creates a uniaxial stress state and shows the adhesive's Young's modulus and strength. For less stiff materials these parameters are not identical with the stiffness of a butt bonded specimen and its technical fracture strength, due to the non-homogeneous and complex stress state.

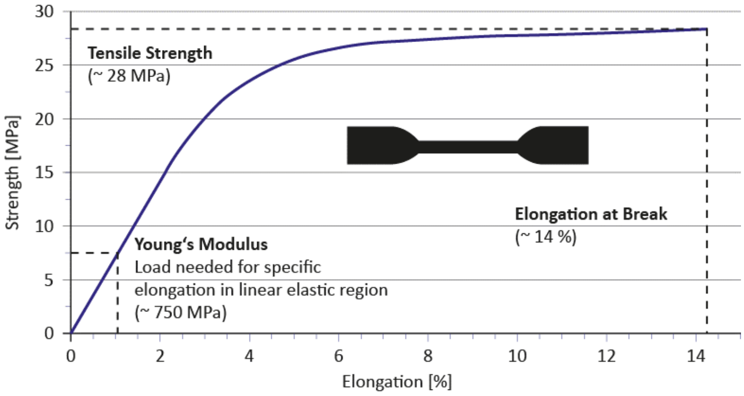


Diagram 7: Dumbbell specimen for tensile testing, technical stress-strain curve

5.2.2 IN-SITU TESTS: STRENGTH, PLASTIFICATION, DAMAGE, CRACK PROPAGATION

Tests with rigid, bonded substrates serve to evaluate the strength in tensile, shear, and combined tensile and shear loading. Information about plastification and damage can be gained.

In comparison to the described tests in 5.1.1, here the stress distribution is assumed to be homogeneous. The use of an optical measurement system to capture the local strain field with the so-called DIC (Digital Imaging Correlation) technique or an FEM analysis (with a linear-elastic or elasto-plastic material law) are helpful to support or refute the assumption of a homogeneous stress distribution.

In fracture tests information about crack propagation is gained.

Butt Bonded Specimen

Butt bonded specimens (**Figure 11**) characterize the in-situ strength, as the cylindrical tensile specimen (tension) and the hollow cylindrical specimen (torsion, tension and combined).

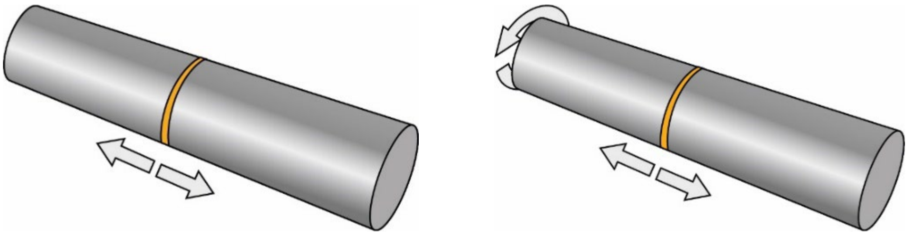


Figure 11: Butt bonded specimens

Thick Adherend Shear Test (TAST)

The shear behavior is evaluated with the Thick Adherend Shear Test (TAST), see **Figure 12**. Substrates may not deform. In this test, a drop in shear strength with increased adhesive thickness is much less pronounced than with the lap shear test on flexible, thinner substrates.

Figure 12: Thick adherend shear test

Adhesive joints are often subject to stress concentrations at the ends of the overlap or the edges. This fact must be taken into account when evaluating mechanical tests and using strength values in the design process. Stiff adherends can be used to reduce stress concentrations and achieve a more homogenous stress distribution.

Fracture Tests

Fracture mechanics tests, developed to characterize the strain energy release rate, the material parameters driving the toughness, are complex to prepare, perform and analyze. Special knowledge and equipment are needed, and a profound understanding of the underlaying theory and the consequent limits of applicability are required in order to determine meaningful parameters. **Figure 13** and **Figure 14** represent a tensile test, the so-called double cantilever beam, where a stable crack growth is observed. Other specimen types (not shown here) allow to investigate the fracture behavior under shear and combined tensile + shear loads.

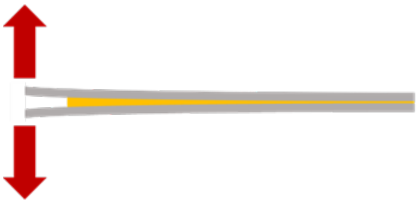


Figure 13: Schematic test representation

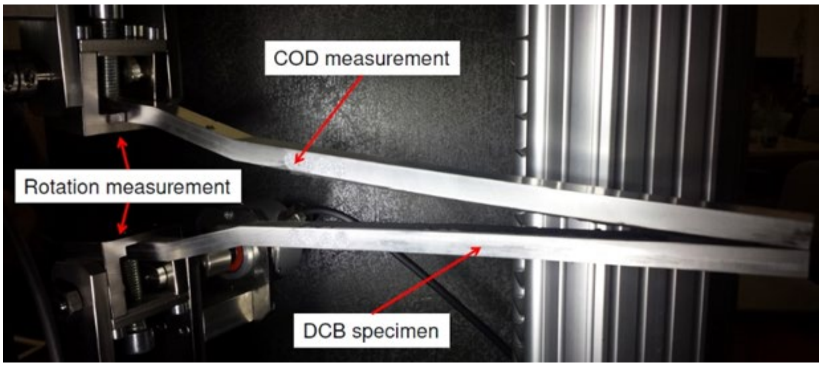


Figure 14: Tensile strain energy release rate measurement, courtesy of IMM (Institut für Mechanik und Material-forschung), Technische Hochschule Mittelhessen

5.3 TEMPERATURE AND STRAIN RATE

In comparison with more flexible adhesives, e.g. polyurethane based, the viscous behavior is less pronounced. In thin, rigid joints the creeping due to constant loads usually does not have to be considered. The change of mechanical behavior with loading at high rates is visible in material tests, but in a complex component the effect is strongly damped and superimposed by inertia effects. The stiffness, strength, ductility, and toughness at temperatures other than room temperature should be considered according to the philosophy of the OEM in developing and proving a structure, and in legal or other release verification tests. A DMTA (Dynamic Mechanical Thermal Analysis) is an easy way to get knowledge of temperature and strain rate / frequency impact in the modulus, or only of frequency impact (testing at ambient temperature and sweeping frequencies from e.g. 0.1 to 100 Hertz, to determine material data for NVH / Frequency Response Analysis). To determine other parameters such as strength or the strain energy release rate – a measure for toughness – more elaborate testing is required.

5.4 AGING AND CORROSION

The nature of polymers is such that their molecular structure, and subsequently the properties change over the time; this effect is increased when materials are exposed to thermal and humidity cycling, along with exposure to salt and to other media. Chemical agents can have a severe impact. Body adhesives with their thin and wide cross section between the metal parts, being entirely enveloped with e-coat and paint, are well protected, compared to other bonded joints, (e.g., screens and attached exterior parts).

Corrosion of metallic adherends can undermine the interface, thus weakening the joint strength.

OEMs have defined tests to mimic the long-term environmental effects in a shortened time (several weeks) on coupon samples. Typically, a strength drop of 20% to maximal 30% is visible and widely accepted. In prototype evaluation phases, vehicles are built up and exposed to harsh driving and corrosion conditions, with a subsequent detailed evaluation of processes and their consequences. In single cases, samples from aged (accelerated or real-time ageing) bodies were extracted and tested, and results were compared to virgin state results: the loss in mechanics was below the loss visible in the accelerated coupon ageing cycles.

> With the polymeric nature of BIW adhesives, a temperature and strain rate dependency of mechanical properties is observed.
>
> Aging due to thermal, humidity and salt spray cycles lowers the properties to a certain extent.
>
> Corrosion undermining of the interface leads to inferior joint behavior.

6 DESIGN

This chapter highlights different joints designs with resulting stress distributions, and shows good practice examples for high load transfer. 5.1.1 gives further explanations to understand the stress state in a joint.

The procedure of adherend assembly and hybrid joining with spot joints is explained with respect to understand the final shape of a bond line.

6.1 DESIGN AND IMPACT ON JOINT STRENGTH

Figure 15 shows a representation of loaded joints and resulting stresses:

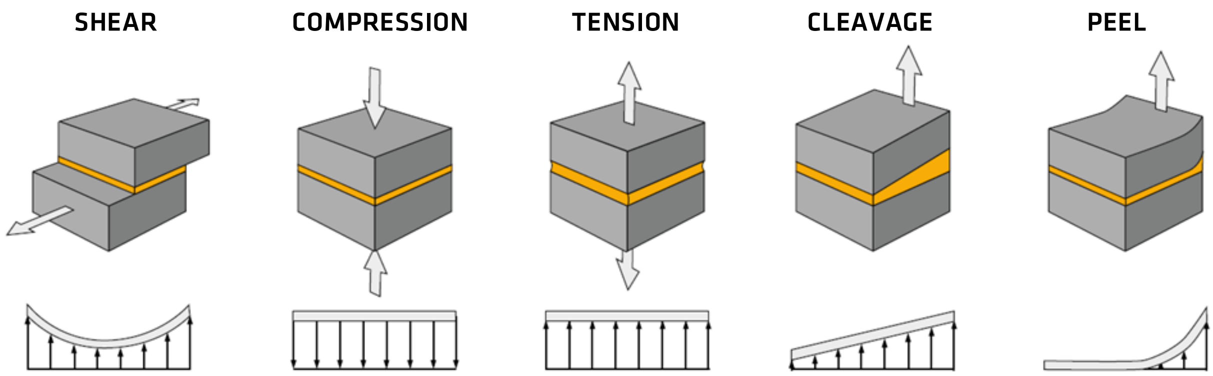


Figure 15: Loaded joints and stress distribution

Since in a vehicle body existing flange and overlap regions - mostly thin metal panels, aluminum castings or extrusion parts - are bonded in addition to the existing spot joints, the design is given. The adhesive is applied to cover the parallel surfaces of the adherends and fill the gap between the joined parts. Typically, the cross section has these nominal dimensions: 0.2 – 0.3 mm thickness, 15 – 20 mm width. According to the load and the mechanical requirements, the width of the joint can be adapted (increased for a larger bond surface and higher load transfer, or decreased for weight saving, considering the stiffening and strengthening effect of bonding). As far as possible, it is recommended to practice certain rules for high load transfer, as listed here below.

THE FOLLOWING GENERAL RULES SHOULD BE APPLIED TO REALIZE STRONG JOINTS:

- Avoid peel and cleavage loads
- Design parts and the joint to transfer peel and tensile into shear loads, and tension into compression
- Target to homogenize the stress distribution (no strong local deformations, especially at the edges of the bond line; usage of stiff adherends)
- Provide large area (length and width)

Generally, it is said that a thin joint performs best – see also 5.1.1 with considerations about bond line thickness.

Figure 16 shows examples of unsuitable and improved joint designs.

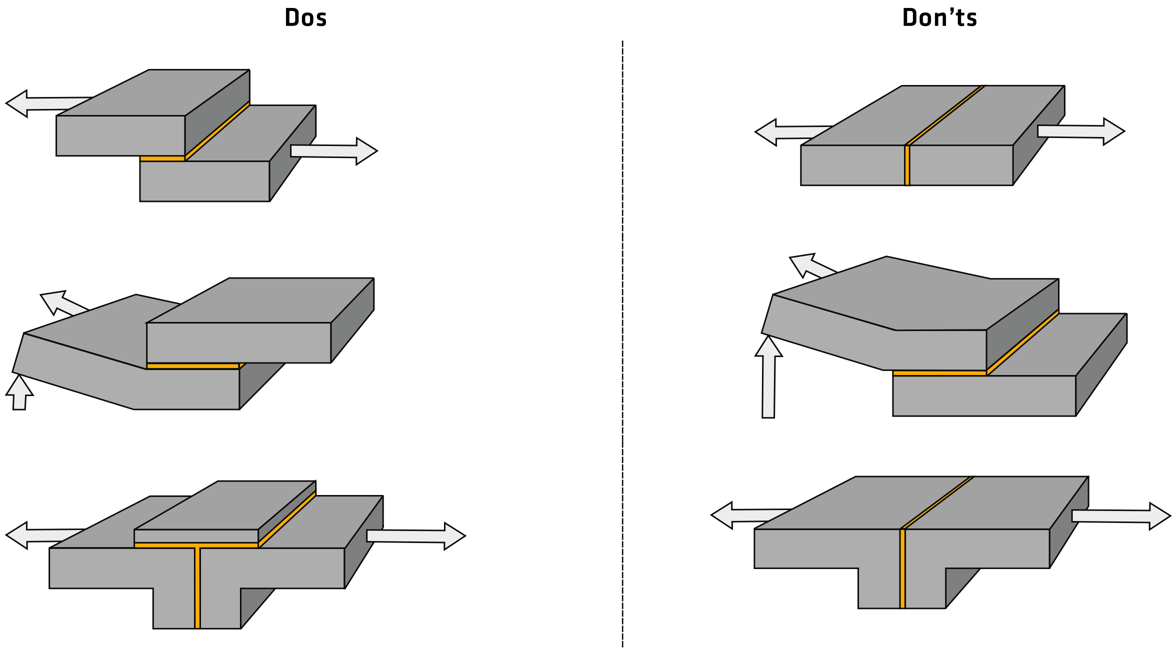


Figure 16: Examples of unsuitable and improved joint designs

In case of an unwanted zipper-like failure of a bonded joint along the length, setting spot joints at the position of crack initiation can prevent the unzipping.

6.2 NOMINAL VERSUS REAL SHAPE

The bond line width and thickness have nominal values, but the real shape is driven by the assembly equipment and process, existence and pitch of spot joints, and adherend stiffness. Here, the resulting, physical shape (thickness, width / flange coverage) of an in-situ bond line is explained. To ensure a minimum thickness and avoid excessive squeeze out, glass bead filled adhesives can be used.

The applied bead on the adherend is stable in its shape and position. It is usually not affected by handling operations (e.g. centrifugal forces, vibrations) after bead application until assembly with the joint partner. With an appropriate assembly direction, the bead is squeezed in a controlled and reproducible way.

Setting spot joints requires a short distance of the adherends, to allow for current flow with RSW and to punch the SPR through the panels. High forces from a welding gun or rivet setter act locally and can displace the adhesive outwards from the spot joint. Using adhesives with glass spheres reduces this displacement and still allows for a stable welding and riveting process.

Due to the SPR or RSW setting forces and the interaction between squeezed adhesive and flexible adherends (thin panels), the final shape can deviate from the nominal cross section, which is called pillowing effect or pocket formation (see **Figure 17**). The pillowing is likely to be stronger in mixed material joints with different coefficients of thermal expansion, where the adherends with the larger expansion exhibits more bending during heating in the e-coat oven, due to the lengthening being blocked by the other adherend with less thermal expansion.

Also, adherend tolerances and dimensional stability affect the bond line cross section.

The normal and tolerable maximum bond line thickness in between neighboring spot joints is about 0.5 mm. Adherend stiffness, and more importantly the spot point pitch (typically 40 mm - 100 mm) are the main drivers for the forming and magnitude of pillowing (shorter pitch = less pillowing). Also, changes in the oven process and BIW throughput affect the magnitude. Setting step beads instead of a continuous bead, which leaves the vicinity of the spot joints open, reduces pillowing. Glass beads in the adhesive can also reduce the opening by limiting the shortest adherend distance (less bending of the adherends). A short distance, typically around the spot joints, can lead to unwanted squeeze out, which can result in e-coat bath contamination by washed off adhesive.

Figure 17 depicts the resulting shape - for illustrative purpose in an exaggerated way -, with respect to cross sectional shape along the joint.

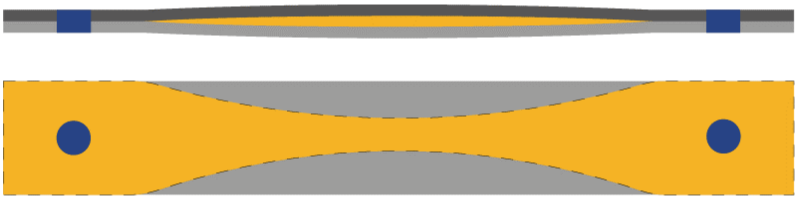


Figure 17: Pillowing effect (exaggerated); grey: steel panels, yellow: adhesive, blue: spot joint

Figure 18 to **Figure 23** show and qualitatively rate the degree of joint filling and squeeze out.

Figure 18: Nominal joint filling

Figure 19: Minimal / under filling

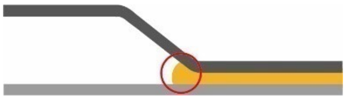


Figure 20: Fillet supported with adhesive, which can have stabilizing effect

Figure 21: Tolerable squeeze out

Figure 22: Massive squeeze out; risk of e-coat bath contamination

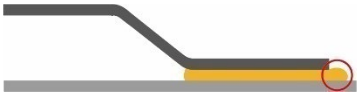


Figure 23: Tolerable squeeze out → stable in wash off and e-coat bath

In CAD and CAE the real shape is not represented. With moderate aberrations, modelling the nominal shape with FEM leads to a sufficiently accurate prediction in many cases. The behavior of a complex component or entire vehicle is also driven by many other constituents and the spot joints; consequently, the effects of deviations from the exact bond line shape are strongly dampened. A sensitivity analysis, reducing or maximizing the bond line width, helps to understand the impact on component or body response.

Efforts are undertaken towards an integrative simulation, considering the entire history, in order to represent the detailed design and any pre-stresses from manufacturing; describing mathematical models and interfaces are constantly developed and improved. Currently, a regular usage in industrial development is not done due to the complexity and time needed to simulate all relevant manufacturing steps and transfer the status from one discipline to the subsequent.

In most flange and overlap joints, the nominal cross section of the squeezed, in-situ bond line is 0.2 – 0.3 mm in thickness and 15 – 20 mm in width. Substantially wider joints can be achieved with higher output rate; thus 50 mm width and higher is possible. Likewise, thicker bond lines are also possible (see 5.1.1).

Nominal and real shape deviate to a certain extent due to the manufacturing process and adherend tolerances; in CAD and CAE the nominal shape is used. Spot joint pitch, glass beads, process parameters have an impact on the deviation.

Severe squeeze out which is subjected to getting washed out in the e-coat bath is to be avoided, as well as severe underfilling of the joint.

Regular inspection on bodies taken out of the production line is advised.

7 STRUCTURAL ANALYSIS

It is assumed that mechanical analyses are performed using FEM. Consequently, indiactions made in this chapter refer to that, not to analytical calculations.

Commonly used epoxy-based body adhesives for structural bonding exhibit an elasto-plastic behavior. It can be divided in the linear-elastic region with Young's modulus and Poisson ratio as the most important describers, and the plastic region above an indistinct yield point, followed by damage and failure at higher deformations; see **Diagram 7**. Unlike metals, where yielding is not dependent on the hydrostatic stress state (volumetric change) but only from deviatoric stresses (shape change, von-Mises stress), both components influence the yield surface and strength. The behavior in tension and compression is asymmetrical; compression in thin, wide applications is seen as uncritical and does not lead to yielding, damage, and failure. Therefore, yielding and strength can be described approximately with a linear or exponential Drucker-Prager law which is implemented in many FEM solvers (more precise material models have been developed and implemented in certain solvers which is not further explained here). Figure 11: Dumbbell specimen for tensile testing, technical stress-strain curve shows a representative stress-strain curve.

In service condition (NVH) stress or strain are usually low and stay in the elastic region; strength is non-critical. Strength investigations are appropriate in certain load cases and areas in the body, such as towing attachment when hauling load or misuse. Fatigue strength often does not require special attention since, as shown in **Diagram 4,** bonded joints are less sensitive than spot joined sheets. For strength analyses, the effect of increased temperatures and aging can be considered with applying reduction factors to the adhesive strength.

Crash simulation is state-of-the-art today with a sufficiently accurate prediction, whereas fatigue strength estimations are still a subject of research and no general method or database exists today.

More information is given in the following.

7.1 FEM MODEL CREATION

In FEM simulations the adhesive is modelled with hexahedron elements with one element layer in thickness direction, corresponding to the nominal physical adhesive width and thickness. The nodes are attached with connection elements / multipoint constraints or tied contacts to the adherends which are represented by shell elements. Alternatively to meshing the adhesive elements with their nominal thickness– for more convenient handling of the thin elements, better aspect ratio or less elements, and for runtime reduction –, the hexahedron elements can reach between the midplanes of the adherends' shell elements.

7.2 STIFFNESS AND NVH CALCULATIONS

The FEM mesh and attachment to the adherends is explained in the following and highlighted in **Figure 24**. The adhesive elements can be attached to one of the adherends with shared nodes, when created with extruding the solid elements from adherends' shell elements, or they can be independent on both sides and attached with distributed coupling (RBE3 elements in Nastran, Optistruct). In this case the modelled thickness is several times higher than the physical thickness. Consequently, density and modulus must be scaled to compensate for the difference and predict correct weight and stiffness, see **Figure 24**.

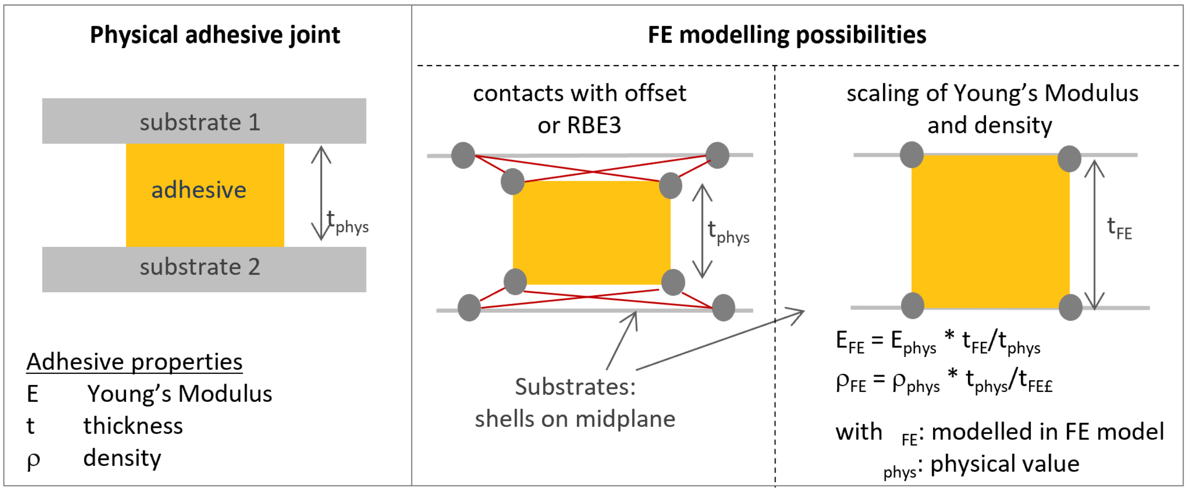


Figure 24: FEM: meshing and connecting adhesive

A linear-elastic material law is to be defined (Young's modulus, Poisson ratio, density). An example of a modal analysis is given in **Figure 25** and **Figure 26** from a study on the public CAE model of the 2001 Ford Taurus.

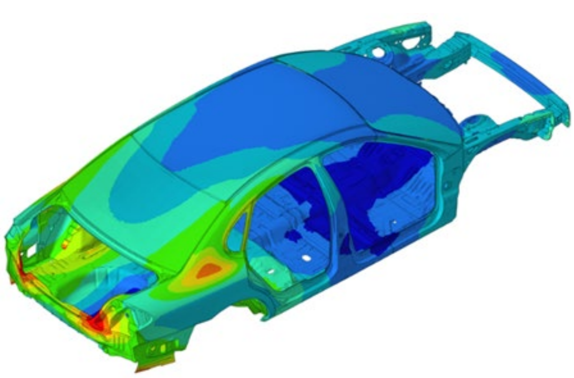


Figure 25: Global bending Eigenform of car body (displacement magnitude, quantitative)

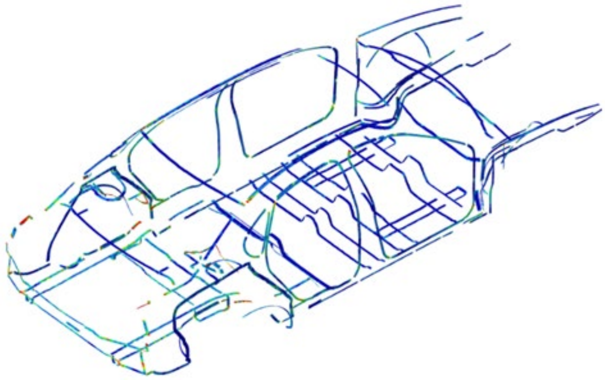


Figure 26: Stress distribution in bond lines (quantitative)

The Young's modulus is influencing the body stiffness, but with increasing the stiffness of the joints (high modulus in a thin, wide bond line) this effect diminishes as the study shows, see **Diagram 8**.

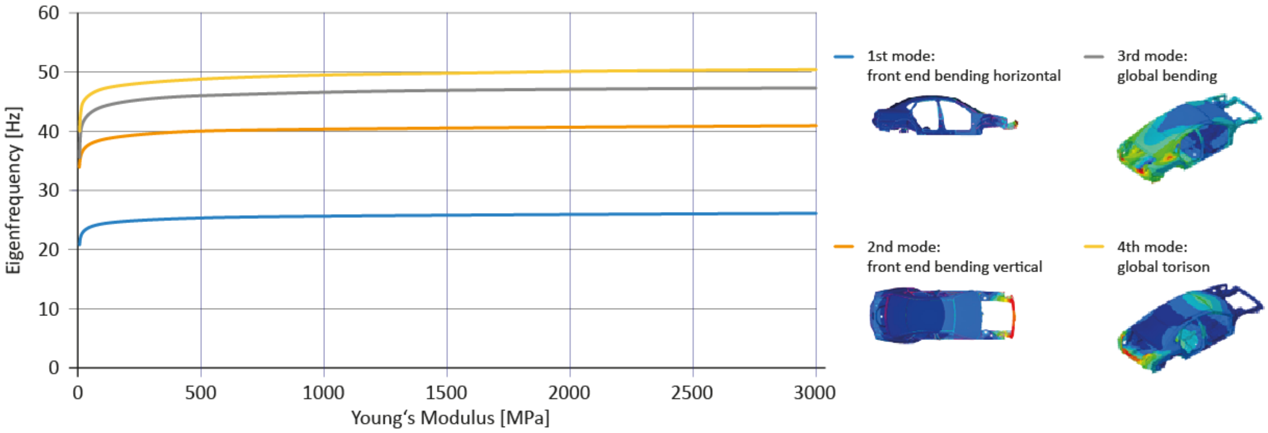


Diagram 8: Impact of adhesive Young's modulus on body stiffness: Eigenmodes and Eigenfrequencies front bending (modes 1 + 2), global bending (mode 3) and global torsion (mode 4) Eigenmodes and Eigenfrequencies

In frequency response analyses, one can assign frequency depending on the modulus and loss factor for more accurate prediction and dampening effect benefits, see also 5.3.

7.3 STRENGTH VERIFICATION

The calculation of local stresses in a bonded joint, mostly done with finite element simulation in the automotive industry, is limited in accuracy due to the small dimensions, limitations in mesh size, and to singularities at the edges of a bonded joint. Also, the differences between nominal and real shape along with the difficulty to represent the real shape, not being straight and forming various notches, poses a difficulty to performing strength analyses (static and fatigue strength).

The fitting of allowable strength values on coupon specimens that were tested and simulated is advisable. The simulated specimen should have the same mesh size that will be used in industrial development. Using representative specimens with regards to bond line dimensions, adherend materials, and adherend dimensions, limits the generality but increases accuracy for the specific application.

Still a stress evaluation is helpful as it allows re-design of adherends and joint to decrease high stresses. And, despite the difficulties, it is used to estimate the loading and safety against failure.

According to the theory of cohesive zones, the stress tensor in a thin layer between two significantly stiffer adherends has two dominant components: 1. normal stress perpendicular to the bond surface (pointing from one adherend to the other) and 2. shear stress in the bond surface. This can be verified with evaluating the simulation results. With the continuum approach, compressive stresses can normally be neglected for a strength analysis; the normal tensile stress σ_{max} and the shear stress τ_{max} acting in one node or integration point can be opposed to the tensile strength σ_a and the shear strength τ_a according to the following equation:

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

Also, with sufficient data, a linear or exponential Drucker-Prager surface can be defined to prove integrity.

The treatment of stress peaks in strength analysis is a frequently discussed topic, but with respect to bonded joints it is relatively new. For that reason, no specific strategy can be proposed, and the common techniques of choosing a critical distance from stress peaks for stress evaluation or ignoring the node or integration point, respectively, with the highest stress is proposed. An elasto-plastic material law can help to estimate benefits from stress redistributions and consequent unloading of highly stressed regions, but this process is limited with stiff, brittle adhesives without a clear ability to yield.

7.4 CRASH SIMULATION

Sika offers a variety of validated material models for crash applications that are provided upon request. Furthermore, Sika can assist in how to implement the material models in the simulation workflow and analyze the results, as well as how to design adherents and joints for improved behavior.

Since the topic of crash simulations is complex and involves a multitude of factors, it is only briefly explained. With the increasing use and mechanical importance of BIW adhesive in the car body, the need for reliable FEM material models and element types raised. The specific challenges of bond line simulations – the small thickness, and the comparatively large width – were responded to with the development of so-called cohesive zone models, which describe the mechanical behavior with a traction separation law in the particular planes (through thickness, in plane) and a coupling definition between the planes. A cohesive formulation allows for meshing the bond line with only one element layer over the thickness and reduces the run time. The traction-separation description (traction or shear stress respectively against adherend separation, other than the well-known stress-strain relation used for many materials) allows to mesh the adhesive layer with a thickness other than the real thickness (e.g., from adherends' midplane to midplane with shell elements). The damage initiation and propagation, for example the appearance and growth of cracks, is described with the parameters of strain energy release rate per unit length – the energy needed to drive a crack through a joint due to tension and shear loads. With that approach, a robust and proven method exists to estimate the loading state of the adhesive elements (linear, plasticized, damaged or failed). It must be noted that the parameter set is only valid for a specific physical bond line thickness.

The parameter identification is done with fracture tests. For validation, special component specimens were developed which are representative for the design and loading, and sensitive to the adhesive behavior whereas the adherends have only a minor influence.

7.5 FATIGUE ESTIMATION

Fatigue strength often does not require special attention since, as shown in **Diagram 4**, bonded joints are less sensitive than spot joined structures. The load is distributed over the large area of the bonded surface; consequently local stress peaks, as present in spot joined only structures, are strongly reduced, which unloads the metal panels and reduces the appearance of fatigue cracks in the adherends. The adhesive globally experiences low stresses only in service conditions; though local high stresses can occur.

The topic of fatigue and durability estimation is still under development. Promising industrially applicable methods exist but must be further proven and optimized. A simplified approach is to use the method proposed above for static strength investigation with reducing the strength according to static and fatigue strength from a Wöhler curve.

8 BONDING PROCESS

In the current document, the most essential topics are shortly explained, as far as relevant for the design process.

8.1 FROM STORED ADHESIVE TO E-COAT BATH

The shelf-life as indicated on the packaging shall not be exceeded. During transport and storage, the temperatures should not exceed 30°C; lower temperatures, even below 0°C, don't damage the adhesive.

As for any bonding process the adherend surface must be in a controlled condition. The common lubricants (oil, hotmelt), applied on panels in thin layers for corrosion protection and drawability, are absorbed by body adhesives during heat curing. Contaminations or other conditions deviating from the nominal state must be avoided or removed.

The open time of the applied bead is limited to a few days or a week (depending on environment conditions). Humidity uptake during this time can negatively affect the mechanical behavior. When the panels are assembled, the uncured adhesive is protected to a certain degree and can usually be handled and stored for several weeks until the curing takes place.

Assembly forces are usually non-critical and only get significant with extremely wide beads or multiple bead applications. After adherend assembly the adhesive is held securely between the panels and is not at risk of being washed out in the e-coat bath. More care must be taken to avoid excessive squeeze out which is vulnerable to wash-out, see 6.2. Special adhesives for warm application require a heated pumping system; once applied and cooled down to ambient temperature again the adhesive has a higher viscosity and therewith good stability and resistance against wash-out.

Setting resistance spot weld points or self-piercing rivets through the adhesive is possible. The process parameters might need to be adapted.

8.2 CURING AND COOLING

The curing takes place in the e-coat oven. The required temperature must be reached – (nominal) oven temperatures often differ from the local temperatures. Due to the limited thickness of the bond line, it can be assumed that the temperature at the adherends close to the adhesive is similar to the temperature in the adhesive - this circumvents the difficulty of measuring the exact temperature in the adhesive (feasible on prototype parts with embedded thermocouples). The curing degree can be examined with a DSC (Differential Scanning Calorimetry) on extracted samples.

With heavy, massive structures as e.g., the sill of battery electric vehicles, the temperature reached locally can fall below the target temperature, leading to insufficient curing. With aluminum structures, e.g., an extruded aluminum profile for sill reinforcement, and their higher heat capacity compared to steel, the shortfall can be significant. Countermeasures are the use of low-bake adhesives or the placement of additional heat sources in the e-coat oven.

Diagram 9 explains the processes during oven heat up, hold phase and cool down with respect to the evolution of temperature, adhesive viscosity and curing, relative displacements of the adherends, and the resulting stress in the bond line, depending on all these parameters.

The adherends move relative to each other, as far as not prohibited by the spot joints. Ideally there are little to no movements, and therewith also no backwards movements during cooling, to avoid shearing or stretching of the liquid adhesive. These relative displacements of the adherends are caused by non-homogeneous temperature distribution; the temperature difference between body panels can be enormous, and the trend to even shorter throughput cycle times with fast heating and cooling increases this non-homogeneity. With mixed materials with different coefficients of thermal expansions, these relative movements get more pronounced and can reach – depending on the length of unconnected regions without spot joints – a magnitude that damages the uncured or cured adhesive (when adherends move back into their initial state during cooling). Shearing of the liquid adhesive can be taken up to a large extent (up to double adhesive thickness / 200% shearing); the stretching can lead to so-called viscous fingering (from about 100-200% stretching on), see 9.1 and 9.2. Indications of these magnitudes originate from detailed investigations with specific adhesives and their general validity is uncertain.

It is difficult to quantify the local relative displacements. The deformation behavior is complex and depending on many variables (adherend stiffness, buckling, pre-deformations, tolerances, interrelations). It is assumed that the cured adhesive with its viscous behavior has a higher tolerance against these deformations than an analytical estimation would propose. Stresses are reduced significantly by the adhesive's ability to creep, especially at elevated temperatures (above the glass transition temperature).

The following steps 1) to 5) explain the process along the time axis.

1) During the heating phase the viscosity of the uncured adhesive is lowered – at this point the spot joints or other fixations are needed to hold the adherends in place, or the bond line has been locally heated before for spot curing. The liquid, pasty adhesive follows the movements of the adherends; the capacity of the adhesive to deform and follow the shear movements is higher than to follow the tensile movements, bridging the gap formed by pillowing, see also 6.2.
2) When temperature in the adhesive has started the curing reaction (this happens at the so-called gel point), the adhesive starts to build up strength and stiffness, and consequently also stresses. Typically, at this phase, the stress level is still low and uncritical, and it is deteriorated during the subsequent hot phase.
3) During the holding phase at nominal constant temperature, the complete curing in all joints and parts of the body takes place.
4) In the first phase of cool down, above the glass transition temperature of the cured adhesive, the adherends move back towards to their initial shape, as far as the now cured adhesive allows. This movement causes stress in the bond line; the stress level is moderate because the adhesive is flexible in this temperature range and creeps, leading to a stress reduction.
5) In the subsequent cool down, below the glass transition temperature, the stiffness of the adhesive is greater, and with prescribed deformations the stress in the adhesive raises. Also, the stress reducing creep process is slower. The creeping still goes on after cooling down at room temperature.

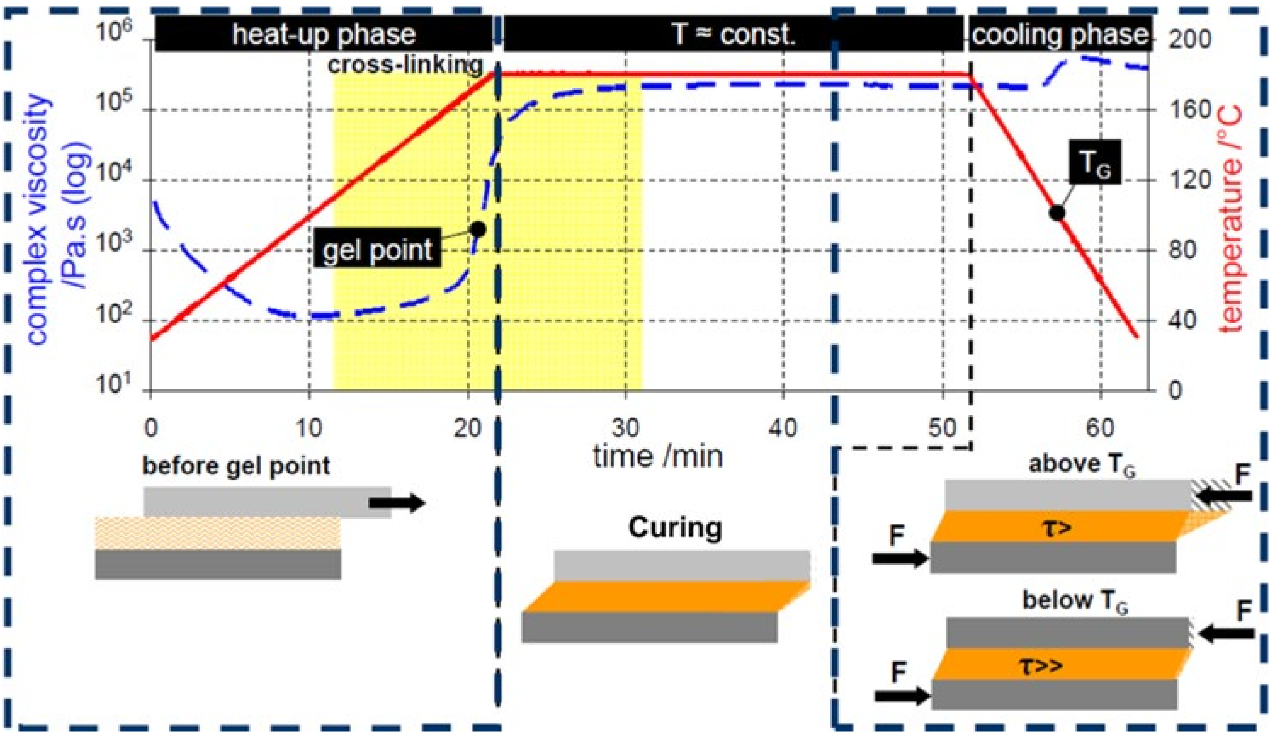


Diagram 9: E-coat oven cycle: temperature and viscosity of adhesive, substrate relative deformation

9 ERROR STATES

To understand the causes of error states, the explanations in 6.2 and 8.2 should be read.

9.1 VISCOUS FINGERING, MEANDER

With too high degree of pillowing the viscous adhesive can't follow the stretching and tears off at certain positions or entirely with extreme flange opening. The fracture surface shows a characteristic pattern, giving the name of Viscous Fingering or Meander to that phenomenon (**Figure 27**). The maximum force which can be transferred is reduced according to the ratio of unbonded to entirely bonded (in ideal state) area. In addition, leakage issues and insufficient corrosion protection are the consequences.

Figure 27: typical fracture surface showing viscous fingering

9.2 HIGH STRESSES OR FAILURE FROM COOLING

Stresses can arise during cooling, see also 8.2. In extreme design conditions, such as mixed aluminum and carbon fiber reinforced composite joints, these stresses can exceed the adhesive strength due to being insufficiently reduced by relaxation or adherend distortion (such distortions are usually unwanted). A bond line failure during curing can occur from these stresses.

9.3 KISSING BOND

A so-called kissing bond can occur with thick beads for gap bridging which have not been pressed down and squeezed sufficiently. From a visual inspection there is contact to both adherends and the joint seems to be established, but the adhesion strength is very low due to insufficient wetting. This only becomes visible with a mechanical test and evaluation of the force, when compared to a properly bonded specimen or the expected force level at failure.

10 QUALITY ASSURANCE

Different measures are taken to guarantee good quality of the bond line.

During the initial validation of the adhesive aspects, the mechanical properties, adhesion, and corrosion resistance was tested and confirmed with different combinations of substrates, lubricants and bake conditions.

After the production of the adhesive, every batch undergoes defined quality assurance tests. The obtained values must be within the set specification prior to the release of the material.

During the application of the adhesive bead, parameters like pressure, flow rate, and temperature are measured and recorded. Using these parameters, the amount of the applied adhesive can be controlled. The position and the geometry of the applied bead can be controlled by a visual inspection system.

After assembly and curing the presence of adhesive along the joint can be detected with slightly squeezed out adhesive (if the application is designed to show that pattern).

After the curing, the bond line can be inspected in two different ways:

a) Destructive tests: in regular intervals the bond line is opened manually. By this the width of the bond line, the adhesion, and error states can be observed. A certain minimum flange filling width to be reached can be defined.
b) Non-destructive tests such as X-ray inspections are very expensive and therefore not used for serial inspection.

11 REPAIR OF BONDED STRUCTURES

Controlled debonding is possible to replace parts and components without damaging the vicinity. A thermal treatment weakens the adhesive in order to disassemble the bonded parts with low forces.

Cooling, most efficiently with solid carbon dioxide, leads to an embrittlement of the adhesive and low resistance to peeling. An industrial process and equipment were recently developed, and the method was proven with various adherend materials and adhesive types:

Link

Heating – for a strength reduction - is a less promising approach, especially in mass intensive areas, since unwanted heat transfer into the adherends prevents a fast, purposeful thermal treatment of the adhesive. Consequences include massive energy consumption, insufficient or slow heating of the targeted bond line, unwanted changings of properties, e.g., in heat treated metals, which could also be plastically deformed when disassembled in a heated state, irreversible processes and damage of other polymeric parts or other bonds.

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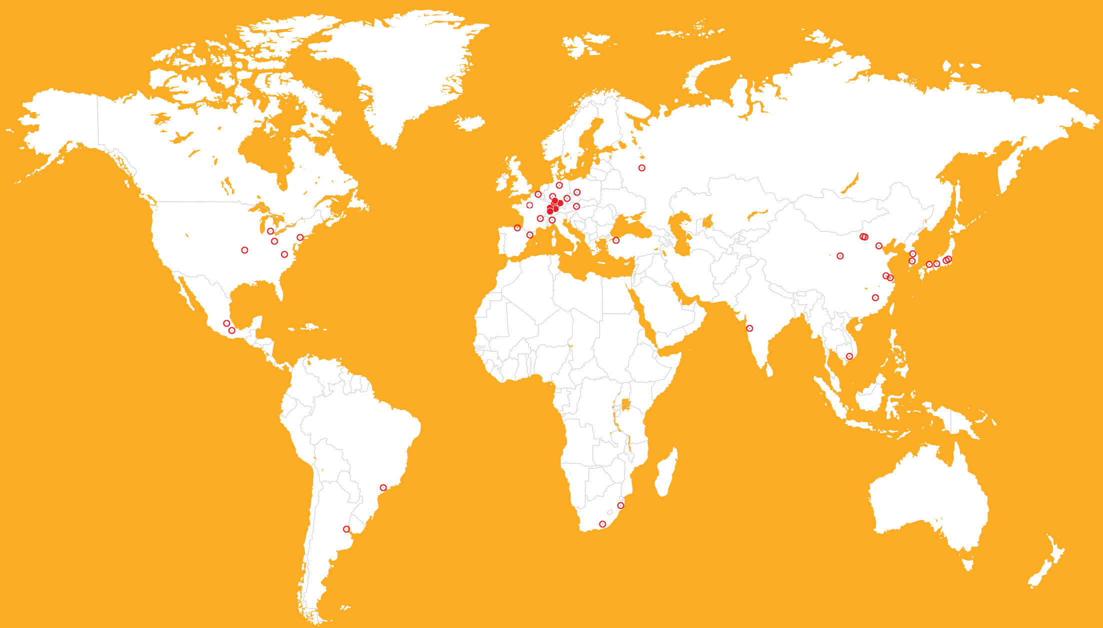

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