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High-Performing Adhesive Bonding Fastening Technique For Automotive Body Structures

Detlef Symietz† and Andreas Lutz

Dow Automotive, Freienbach/Switzerland
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Abstract: In modern vehicle construction the search for means of weight reduction, improving durability, increasing comfort and raising body stiffness are issues of priority to the design engineer. The intelligent usage of many materials such as high strength steel, light-alloys and plastics enables a significant vehicle weight reduction to be achieved. The classical joining techniques used in the automobile industry need to be newly-evaluated since they often do not present workable solutions for such mixed-material connections, for example aluminium/steel. Calculation/simulation methods have made progress as a key factor for broader and more cost-effective implementation of structural bonding. This will lead to reduction of spotwelds and accelerate the car development. A special focus of the paper is the use of high strength steel grades. It will be shown that adhesive bonding is a key tool for yielding the potential of advanced high strength steel for low gauging without compromising the stiffness. The latest status of adhesive development has been described. Improvements with physical strength and glass temperature as well as of process relevant properties are shown. Also the situation regarding occupational hygiene is treated, showing that by further spotweld point reduction the emission around the working area can be even lowered against the current praxis. High performing lightweight design cannot longer do without high performing crash durable adhesives.

Keywords: *Crash durable adhesives, dynamic durability, body stiffness, calculation methods, occupational hygiene*

1. Introductilon

After now more than five years experience with crash durable adhesives in the car one can state that the high expectations have been fulfilled. The combination with other classical fastening methods, preferably spotwelding, is an ideal approach: The immediate strength comes from the one method, the bonding delivers the excellent durability, higher stiffness, better NVH comfort and material mix possibilities.

A definition for the different performance types of structural adhesive will be given. This helps to classify the adhesives and is a differentiation to any other adhesive products, for example direct glazing adhesives, which are often called too as structural adhesives, but shouldn't be mixed.

An innovative toughening approach using two mechanism with a synergistic result are the basic for the unique properties. Properly designed, even high strength steel is plastically deformed under crash situation without destroying the bond. Reasons are the uniform stress distribution over the large bonding area.

The field experience over the last years accelerated the adhesive development. New generations with improved rheology, higher impact strength at low temperatures and very low water sensitivity in the uncured state are available and in use already.

Progress has been made with calculation/simulation methods to predict the behaviour at an early stage of the car design. The resistance against crack propagation is the key for the performance. This phenomenon can be described by the new FEM simulation tools.

†Corresponding author: email : dsymietz@dow.com

Table 1. Classification of structural adhesives

Classification	Mechanical and Physical Properties	Technology
CDA	Young's-modulus [MPa]: 1400～2000 Elongation at break [%] > 8 Lap shear strength [MPa] CRS 1.5 mm > 25 Coated steels 0.8 mm > 20 Aluminium, pretreated > 20 Impact Peel Strength at $23^{o}C$ [N/mm] CRS 1 mm > 35 Coated steels 0.8 mm > 35 Aluminium, pretreated > 30 Impact Peel Strength at $-40^{o}C$ [N/mm] CRS 1mm > 20 Coated steels 0.8mm > 20 Aluminium, pretreated > 20	SRT
Semi-CDA	Young's-modulus [MPa]: 2000～3000 Elongation at break [%]: 5～8 Lap shear strength [MPa] CRS 1.5 mm > 22 Coated steels 0.8 mm > 18 Aluminium, pretreated > 18 Impact Peel Strength at $23^{o}C$ [N/mm] CRS 1 mm > 15 Coated steels 0.8 mm > 15 Aluminium, pretreated > 15 Impact Peel Strength at $-40^{o}C$ [N/mm] CRS 1 mm > 8 Coated steels 0.8 mm > 10 Aluminium pretreated > 10	SRT
Basic Structural Adhesive	Young's-modulus [MPa]: 4000～6000 Elongation at break [%] < 5 Lap shear strength [MPa] CRS 1.5 mm > 20 Coated steels 0.8 mm > 15 Aluminium pretreated > 15 Impact Peel Strength at $23^{o}C$ [N/mm] < 10	Simple (functionalized) rubber or core-shell-rubber technology

2. Definition and Classification of Structural Adhesives

2.1. Definition of Structural Bonding

So far there is no universally accepted definition of the term "structural bonding". Each discipline develops its own vocabulary. One can find for example the key word "structural bonding and sealing". But also for the special application case automotive manufacturing no clear definition does exist. Our proposal is:

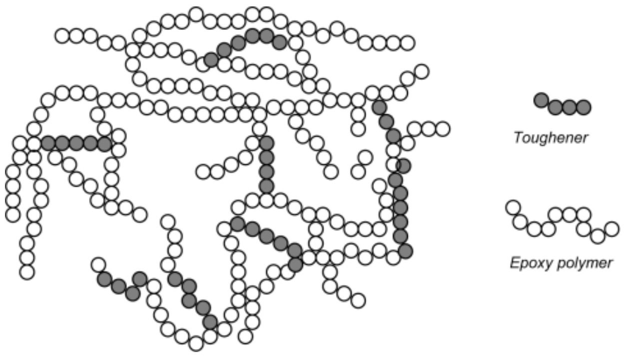

Figure 1. Principle of toughening.

- Structural adhesive bonding in the automotive body shall mean a durable, permanent, loadbearing and stiff connection of stiff body parts.
- Durable in this sense means to be working for the full life of the vehicle (parking about 100,000～300,000 hours, riding about 5000 hours).
- Stiff connection means for the Young's modulus of the adhesive a level of about 1,000 MPa, and for the body parts to be bonded an order of about 100,000 MPa.
- Crash Durable Adhesives (CDA) are such structural adhesives which are designed to resist significant crash loads.
- Semi-CDA have a moderate level of impact strength at all relevant temperatures
- Basic Structural Adhesives have high modulus and high strength to meet the stiffening function, but they perform brittle.

This quantification enables a clear distinction to be drawn between structural bonding and all other forms of bonding in the vehicle, for example direct glazing.

The working principle is that the strength and toughness level of the adhesive so high that in case of high impact loads the metal will be stressed above the yield stress and the bond will not fail.

The energy absorption is caused dominantly by the metal deformation. The adhesive's amount itself is of minor importance.

A new, innovative toughening technology was needed to get such performance. The brittle epoxy resin is toughened by an unique combination of two toughening mechanisms and is called Synergistic Rubber-Toughening technology (SRT).

Table 1 shows figures for impact peel strength, quasistatic lap shear strength and Young's modulus for the three performance classes.

Table 2. Dynamic resistance coefficients for steel grades with different yield strength

Yield Strength Rρ0.2 (MPa)	Dynamic Resistance coefficient k (Ns/m)
180	1600
300	1100
380	800
450	600
700	400

Table 3. Energy absorption of steel grades at different impact speed (thickness 0.8 mm, deformation 150 mm)

Impact Speed (m/s)	CRS (Rρ0.2=190 MPa) Absorbed Energy (kJ)	HSS (Rρ0.2=420 MPa) Absorbed Energy (kJ)
2	2.5	4.1
5	3.5	4.5
10	4.3	5.0
20	5.6	5.6

Table 4. Shear strength and energy absorption (BETAMATE™ 1496, CRS 0.5～6.0 mm)

Steel Thickness	Shear Strength	Energy Absorption
0.5 mm	14 MPa*	120 J
1.0 mm	25 MPa (CF)	44 J
1.5 mm	33 MPa (CF)	20 J
6.0 mm	40 MPa (CF)	3 J

*:substrate failure; CF: cohesive failure

3. The Toughening Technology

One can say that not the strength of a plastic material is the key for mechanical durability, but the toughness. Under impact load locally high stresses will induce cracks. The deciding factor for performance is whether the crack growth can be hindered or stopped. The SRT technology uses also chemically into the epoxy matrix linked toughener islets. Figure 1 shows the principle.

Important is that the flexible toughener eliminate the brittleness at low relevant ambient temperatures but without compromising the high modulus. The working principle of this toughening technology is that energy density will be reduced throughout the adhesive by distributing the energy over larger areas. So the local concentration level is lowered. This phenomenon is known in fracture mechanics as cavitation. A high number of tiny cracks dissipate the energy. But we must

Table 5. Spotwelding vs. adhesive bonding (energy absorption, max. forces)

Joint Material	Spotwelding: Max. Force (N)	Spotwelding: Energy Absorption (J)	Bonding: Max. Force (N)	Bonding: Energy Absorption (J)
CRS, 0.9 mm	5050	10.5	8750	166
CRS, 1.5 mm	6450	11.9	12150	25

TM: Trademark of the Dow Chemical Company
(Bonded area 25 mm × 10 mm, impact speed 5 m/s, 23^{o}C; one spotweld)

keep in mind that this process causes the non-brittleness, but it shouldn't be mixed with the energy absorption of the car body segment during crash.

3.1. Energy Absorption

Under crash situation the kinetic energy must be dissipated my the deformation work of the metal. The adhesive bond must only be strong and tough enough to make this metal deformation happen. The CDAs using the SRT technology do this also for new high strength steel grades. Fortunately the dynamic resistance coefficient k of steel grades is lowered with increasing yield strength $R\rho 0.2$. Table 2 shows such Figures.

The strength of steel, as well known for polymers, is increasing with increasing deformation rate. But the energy absorption of unalloyed steel and high strength steel (HSS) is coming closer together for higher impact speeds. At 2 m/s the difference may be, for example, 100%, at 20 m/s the energy absorption figures will be almost the same. Table 3 gives an example, tested with MIG welded crush samples.

We see in table 4 the dominant meaning of the metal deformation for energy absorption. The figures vary from 3 Joule to 120 Joule for the same adhesive. The metal deformation can be reached for all reasonable metal thicknesses by proper joint design. For the shown figures the bonded area (25 mm × 10 mm) has been unchanged, so the shear strength is increasing, the energy absorption is lowered by less metal deformation.

4. Structural Bonding in Comparison to State of the Art Joining Methods

This topic will be treated by two examples, impact shear and dynamic fatigue.

4.1. Energy Absorption: Spotweld Joints Versus Adhesive Bonded Joints Under Impact Shear

Figures are given in Table 5.

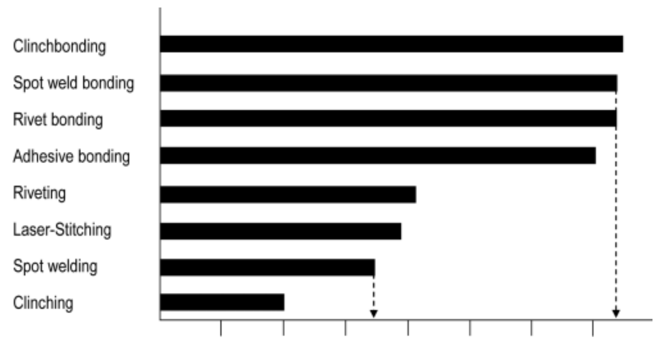

Figure 2. Dynamic fatigue performance of various fastening techniques.

The applied small bonding area is good for lower steel thicknesses, then the superiority of bonding is clearer to see. The energy absorption is higher by a factor 15!

4.2. Dynamic Fatigue: Comparison Between Various Fastening Techniques

With high strength steel connections have been made with various joining techniques, including hybrid bonding. The number of cycles to failure are shown in Figure 2. One can see that the fatigue performance of bonding (single, hybrid) is tremendous higher than the "classical" fastening methods. For comparison purposes the results for spot welding and spot weldbonding are marked.

The field experience over the last years confirms the dynamic-mechanic durability of structural bonding by very little lowering of the body stiffening over the service time in comparison to just spotwelded bodies.

5. Special Aspects

5.1. Calculation/Simulation

To use the full potential of structural bonding, calculation/simulation of adhesively bonded joints is a must. Objectives of simulating bonded joints is to examine the

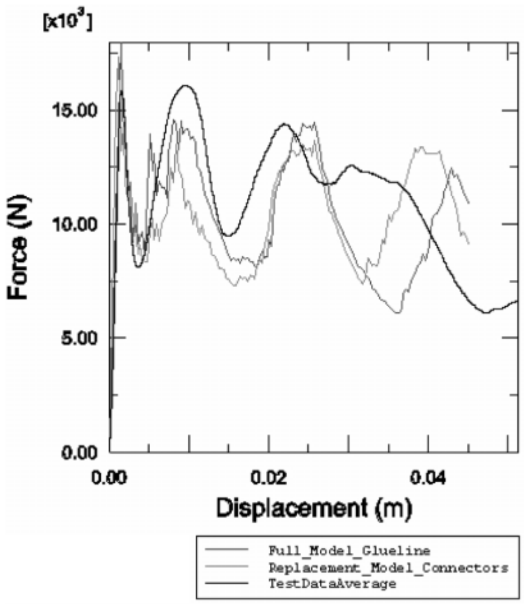

Figure 3. Force-Displacement for double hat crushing (model vs. test).

adhesive properties and the stress distribution throughout the adhesive layer for linear and non-linear deformation.

This reduces the experimental efforts and helps to get an optimized joint design. Currently the structural bonds are mostly overspecified. One knows examples where the increased body stiffness of bonded cars was unchanged in case of spotweld reduction by 50 percent. Progress has been made with development of specific mathematical methods. Figure 3 shows an example for calculated and measured force displacement for a double hat crushing with rather good coincidence.

5.2. Quality Assurance

Quality assurance has priority over quality control. Therefore process control must include:

- Automatic application
- Monitoring the adhesive amount and the adhesive bead geometry
- Securing the right application without interruption with the right temperature
- Controlling by vision systems that the adhesive bead is applied at the right place.

5.3. Occupational Hygiene

The situation in case of application of new crash durable structural adhesives is quite similar to the use elder standard structural epoxy adhesives. Literature search shows that during spotwelding through the adhesive the pyrolysis products are practially the very similar to those emitted by oily sheet welding. The number of spotwelds can be reduced, for example by 50 percent due to the high performance, so at the end the overall emission can be even reduced.

6. Summary

Application of the discussed crash durable adhesives for structural bonding is a relevant tool to meet high-priority needs of car manufacturers:

- Lightweight design by down gauging
- Ease of material mix
- Higher durability
- Higher body stiffness
- Better crash performance
- Lowering the function cost