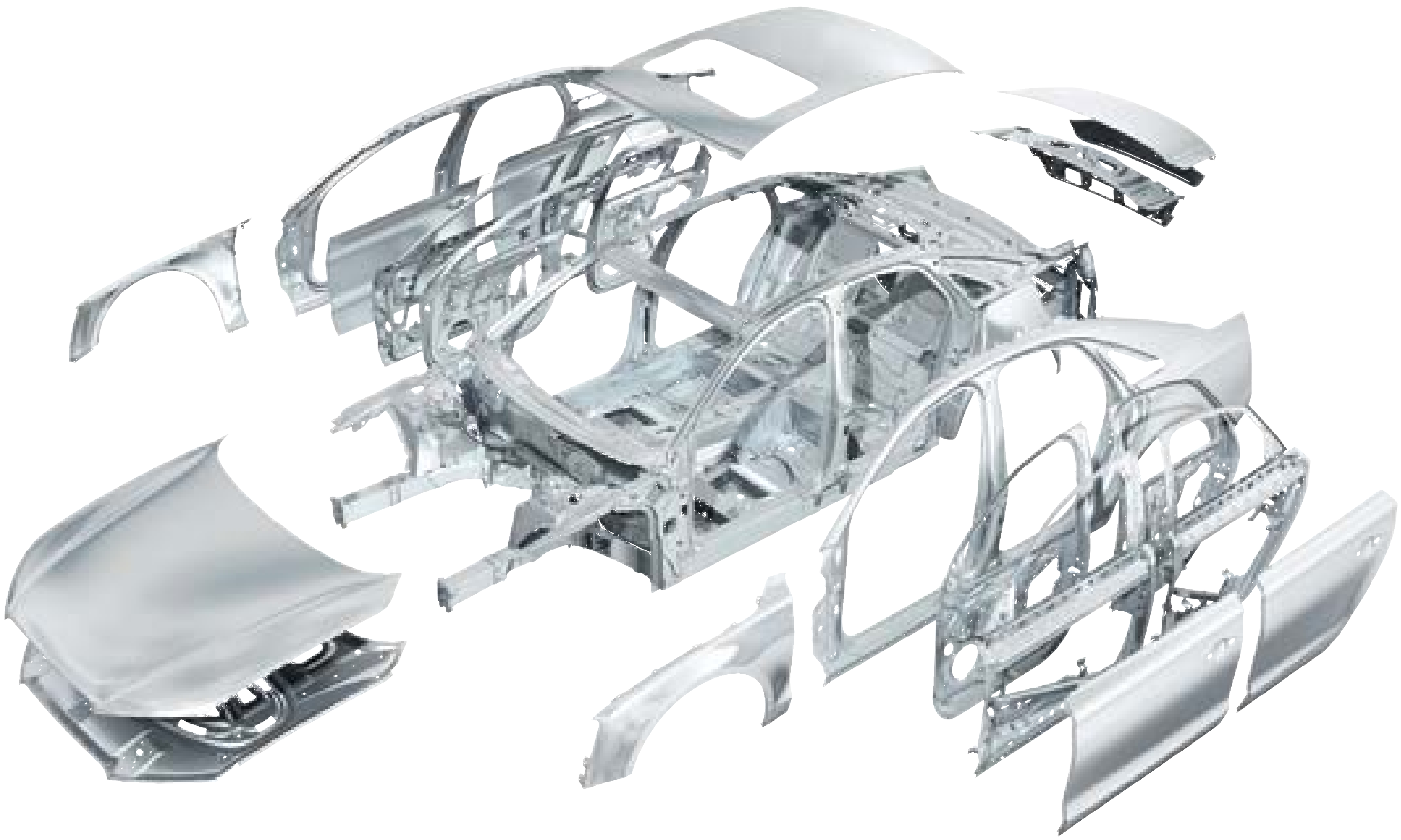
Solutions from DuPont

Structural Bonding of Lightweight Cars

Crash durable, safe and economical



"Without the use of bonding technology, modern lightweight designs would hardly be feasible – especially when it comes to bonding dissimilar and/or new materials."

—Dr. Andreas Groß, Advanced Training and Technology Transfer, Fraunhofer IFAM

Technology Meets Lightweight Construction

Dear Readers,

The automotive industry has in recent years successfully attempted to build lighter vehicles with more fuel-efficient engines in order to significantly reduce fleet consumption in accordance with legal requirements. Significantly lower fuel consumption and CO_2 emissions have been the immediate payoff of such developments.

Improved fuel consumption, environmental friendliness, driving comfort, and safety therefore feature among the sales arguments many car manufacturers now employ for their marketing strategies.

Automotive suppliers and material manufacturers support car makers in developing modern lightweight designs and respond to questions concerning the potentials of current technologies and materials to satisfy challenging future requirements.

In this context, industry experts assume that steel will remain the primary material for vehicle structures. However, new high-strength steel grades are finding their way into vehicle structures. Metals with low density such as aluminum and even magnesium are increasing in demand – as are polymer materials such as fiber-reinforced composites.

Fuelled by the importance of those very diverse materials, questions regarding bonding technology enter center stage of the discussion. This is the key interface between lightweight construction and bonding technologies for new vehicle designs.

Modern lightweight designs require new bonding technologies in addition to new materials and/or an increased material mix. Bonding is of special importance here. It enables the use of new materials, new material combinations and it provides structural advantages for bonded components.

Please review the following technical summary to learn more about the status quo of existing concepts as well as new potential development in adhesives and foams for use in modern lightweight vehicle construction.

I wish you a fascinating read and successful bonding!

Dr. Andreas Lutz
Head Developer
"Metal Bonding Europe"
DuPont
Horgen, Switzerland

The Key to Making Lightweight Cars

Innovative lightweight designs in vehicle development

Modern lightweight designs require new bonding technologies in addition to new materials and/or an increased material mix. Bonding is of special importance here. It enables the use of new materials, new material combinations and it provides structural advantages for bonded components.

1.1 Weight reduction for meeting future legal standards

Two main factors drive vehicle weight reduction. In addition to the future maximum values for CO_2 emissions as expressed in the EU Directive 443/2009, an increasing number of countries are planning road-usage fees based on such emissions. Both factors in combination with increased fuel prices result in a strong motivation to purchase low-emission vehicles.

Fuel consumption can be lowered by a number of different methods. Lightweight vehicle construction is a significant factor throughout, immediately contributing to reducing fuel consumption. Savings by down gauging vehicle components such as powertrain, engine, and underbody yield further secondary effects. Various studies show that a 100 kg weight reduction results in reduced emissions of 5.0 to 12.5 g of CO_2 (ca. 3 to 7 %) per driven kilometer.

Representing approximately 40 percent of total vehicle weight, the car body is the heaviest vehicle element. The consequent implementation of lightweight measures in the car body appears therefore very effective. Increasing demands regarding stiffness, acoustics, crash performance and long-term stability are generally in conflict with lightweight construction and underline the complexity of this challenge.

1.2 Current trends for reducing vehicle weight

Several methods for weight reduction are available. The three most important approaches are:

1. Use of low-density materials
Aluminum, magnesium and plastics/thermoset composites are often used in mounted parts and covers. According to a statement by the Aluminum Association Inc., aluminum contributed to an average of 7.8 percent of the total weight for passenger vehicles in the year 2009.

2. Targeted use of high-strength materials
High- and highest-strength steels are solutions for wall thickness-reduced components. Tailor-welded or tailor-rolled blanks are related technologies that make use of this principle.

3. Integrated lightweight construction
This is a combination of various materials and functional characteristics based on the use of bonding technologies and production processes.

The most significant lightweight construction trend over recent years is the use of high-strength steel (HSS). Even vehicle bodies of the European compact car class now contain a HSS share of 50 to 65 percent. Without exception, the safety cells of today's cars consist mainly of HSS. Tailor-welded or tailor-rolled blank technologies are consequently used for further optimization.

Another significant trend is the use of thermoplastics and thermoset composites in bonded roof components, hoods, trunk covers and some body-structure components. As the article will describe in further detail, bonding technology could also solve the challenge of joining various metallic and non-metallic materials.

1.3 The path toward a balanced car body

As mentioned above, reducing the body weight, while simultaneously increasing performance, is a complex task. The following elements are key demands when developing innovative solutions:

1. Increasing the static and dynamic stiffness to improve the general vehicle quality and to optimize driving and handling characteristics.

2. Reducing vibrations and noise (noise, vibration, harshness and acoustics).

3. Optimizing crash behavior to comply with legal and voluntary safety guidelines (EG: NCAP safety testing)

4. Extending vehicle life span and long-term value via higher quality and retained driving characteristics.

Improvements in those four areas are by no means the only challenges when reducing vehicle weight. A new vehicle generation often requires the development of greater passenger space. Consequently, new vehicle models are rarely lighter than their predecessors.

1.4 Potential and limits of current technology trends

Five years ago, mild steel contributed between 40 and 50 percent of body shell weight. Today, new vehicles generally contain a mild steel share not exceeding 20 to 25 percent. Now, materials include mostly HSS and increasingly, aluminum. Using HSS and ultra-high-strength steel (UHSS) allowed wall thickness reductions up to 0.5 mm. However, it is unlikely that such steel grades can further increase the structural optimization potential.

Particular weight-reduction measures such as tailor-welded or tailor-rolled blanks have in the meantime also become a standard in compact cars. When considering the strongly rising aluminum share on top of that, it becomes clear that additional new technologies will be required to further reduce weight.

2 Status quo of structural bonding in the vehicle body

Structural adhesives and structural foams (see chapter 5) are polymer solutions offering a great potential for body-weight reductions: *Figure 1*.

Such technology concepts allow for additional performance improvements even in already-optimized body structures. These methods will be explained in more detail below.

2.1 Structural bonding of uncoated metal substrates

Structural bonding signifies permanent and stable bonding increasing the overall efficiency and effectiveness of a conventionally joined structure. For current automotive metal bonding applications more than 95 percent is based on epoxy adhesives. This is due to the combination of various advantageous characteristics such as oil absorption capacity, durability, and outstanding mechanical characteristics across a wide temperature range.

Structural bonding in vehicle construction is used in the following areas:

- Joining non-weldable and/or heat-sensitive components and materials
- Construction components that are hard, or impossible to access with welding devices
- Joining various metallic and non-metallic substrates with regard to avoiding galvanic corrosion
- Reducing cycle times and costs by reducing spot welds
- From experience, the use of structural bonding allows the following general performance characteristics:
  - Increasing static stiffness between 8 and 15 percent
  - Increasing dynamic stiffness by 2 to 3 Hz
  - Increasing joint durability by 100 up to 10,000 percent

Special impact resistance-modified epoxy structural adhesives, so-called crash-durable adhesives (CDAs), yield additional load-path optimization, thus further improving a vehicle's crash behavior. Unnecessary performance potential can often directly be used for further weight reduction by downsizing the involved structures.

In addition to the established epoxy systems, innovative rubber-based structural adhesives with glass-transition temperatures of over 90 °C are becoming increasingly popular due to an attractive cost-benefit ratio.

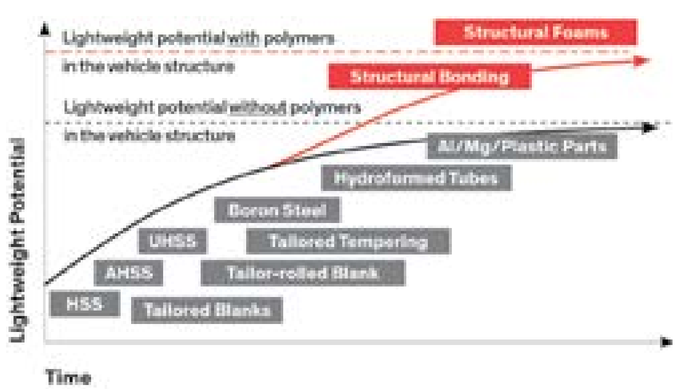


Figure 1 - New weight-reduction potential with structural adhesives and structural foams.

2.2 Structural bonding of composite materials

When joining composite components, mainly two-component polyurethane (PU) adhesives (2K-PU) are used. PU adhesives are characterized by high strength and stiffness values at high elongation levels. This results in very positive impact and fatigue properties of bonded joints.

The use of bonded composite components offers the following advantages:

- Significant weight savings compared to conventional designs
- Design and functional integration leading to a reduced number of components
- Lower tooling costs compared to metal pressings and thermoplastic welding technologies
- High damage tolerance compared to aluminum and steel materials
- Very good corrosion resistance

As shown in *Figure 2*, composites are frequently used in hoods, trunk lids, hang-on parts and floor applications.

PU-based structural adhesives allow joining these components in the vehicle assembly. To meet different requirements, numerous adhesive systems are available. Compared with conventional joining techniques a number of key aspects must be considered when selecting a structural adhesive:

- Consideration of assembly directions, joining and curing times
- How joint geometry and material selection correlates with load case
- Possible required surface preparation
- Dissimilar thermal elongation coefficients
- Stress/strain limitations

Advanced structural adhesives will help to optimize strength and elongation levels of bonded composite components and create new applications for crash-relevant components.

3 Trends in structural bonding of non-coated metal substrates

Over the last ten years, CDAs have developed from a regionally applied adhesive technology into a globally applied solution. They are mainly used for vehicle structures and hem flanges for closures. Their positive contributions, which have by now become known and acknowledged, have improved several car characteristics, such as higher stiffness, improved crash performance and enhanced durability. The CDA technology furthermore enables the development of lighter structures and bonding of new materials such as UHSS or composites. Future regulations will not necessarily require the development of new formulations, as today's products already provide first-rate mechanical performance levels. The future will therefore rather be about developing materials that further improve application and processing.

Figure 2 - Potential application areas of bonded hybrid composites.

3.1 New requirements for structural adhesives

CDAs are used globally in the vehicle body structure. The market demands robust technologies that must meet the most diverse process requirements as outlined below:

Bonding galvanized steels

Today, many different steel grades are used in vehicle construction, and the share of HSS and UHSS is peaking. The surfaces of these steels are usually galvanized. One disadvantage of such coatings in combination with higher-strength steels is it's tendency toward layer delamination under strain. CDAs bond these steels very effectively and significantly increase the durability of joints, when compared to traditional methods such as spot welding.

Bonding of galvaneal steels

Crash-resistant structural adhesives bond very well to hot-dipped and electrolytically galvanized coatings. However galvaneal coating layers have a tendency to delaminate under strain even for lower grades of steel. The development of special structural adhesives is therefore necessary.

Optimal temperature resistance

Adhesives are now widely used in different climates. Often they are stored for many months prior to application and constant storage conditions cannot be guaranteed. Independent of storage considerations, adhesives should be easily applicable with modern processes like jet-spraying. For these purposes, high temperature-stable CDAs have been developed.

Optimal processability: good adherence, compressibility and gap filling

Good initial tack is necessary for oily metal substrates. This especially applies during winter when surfaces can become colder than 15 °C and the drawing oil has a greater viscosity. Good adhesion must also be ensured on the opposite metal surface.

	New-generation CDA	Former-generation adhesive
E modulus (MPa), ca.	1500	1600
Elongation at break (%), ca.	20	13

Table 1 - Adhesive nominal values comparison of former- and new-generation crash-resistant structural adhesives.

When joining the components, the adhesive must have a good flow and squeeze behavior in order to optimally fill gaps.

Components such as doors rarely have constant gap dimensions. The adhesive must be able to fill the spaces resulting from these gap variations.

The adhesive's rheology must be perfectly tuned to the process requirements.

3.2 Modern crash-durable epoxy adhesives for structural bonding

In the meantime, new CDAs have been developed that meet all of the above requirements and are being supplied globally.

Bonding HSS and UHSS

Compared to previous structural adhesives (see Table 1), new-generation adhesives show greater elongation at break, reduced bonding strength loss after corrosion, and reduced loss of dynamic peel strengths at lower test temperatures and for higher-strength steel grades.

Figure 3a shows the stability of impact peel values of various steel grades at test temperatures between +23 °C and -40 °C. Compared to former-generation structural adhesives, the loss in impact peel strength is very low for higher-strength steel grades and at low temperatures. The improved flexibility of the new-generation adhesives is evident in *Figure 3b* displaying the impact peel strength of bonded steel samples of medium strength at various temperatures below 0 °C. Even at temperatures below -40 °C, the values remain remarkably high. In addition, these adhesives display an excellent corrosion resistance.

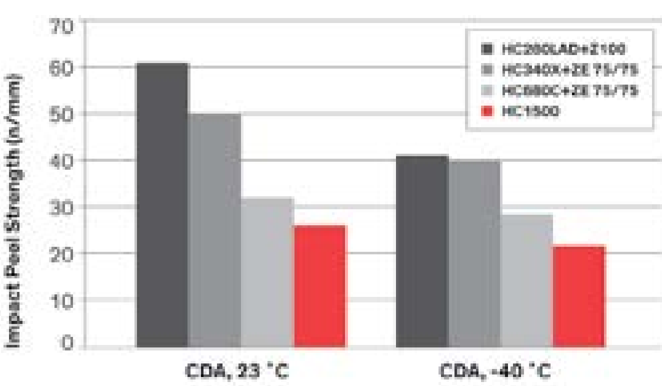


Figure 3a - Impact peel strength depending on steel grades and test temperatures.

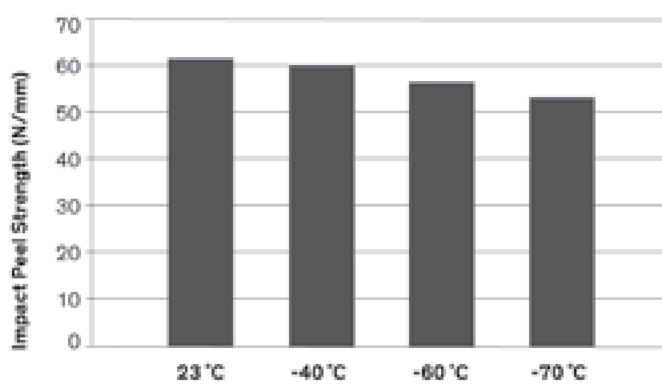


Figure 3b - Impact peel strength for various test temperatures.

Bonding galvaneal coated steels

Bonded galvaneal coatings tend to delaminate under strain. This tendency is greater for shear loads than peel strains.
New generation CDAs display a robust cohesive failure mode on galvaneal surfaces without impacting quasi-static shear and dynamic peel strengths.

Table 2 summarizes the results of the new-generation adhesive and compares this material to a former-generation adhesive. Adhesive characteristics and shear strengths are comparable but dynamic impact peel strengths have significantly improved.

	New-generation CDA	Former-generation adhesive
E modulus (MPa), ca.	1400	1600
Elongation at break (%), ca.	12	13
Impact peel strength*(N/mm)	32	21
Shear strength (MPa)	23	22

*Impact peel strength SCGA 270, 1 mm; shear strength SCGA 270, 1.6 mm

Table 2 - Adhesive and mechanical characteristics for a galvaneal-optimized adhesive.

Bonding aluminum

To ensure robust long-term durable bonds and assembly, a systematic approach to selecting adhesives, pretreatment, and lubricant is necessary during the design/development process. And, key challenges such as potential component distortion due to thermal and mechanical loads, the impact of residual stresses on adhesion-performance strength, fatigue/durability and corrosion must be examined.

To overcome these challenges, BETAMATE™ epoxy-based and BETAFORCE™ polyurethane-based structural adhesives from DuPont are customized for body, paint and trim shop assembly and repair, with the key differentiator between formulations being the typical temperature excursion and duration. For example, components assembled in the body shop are typically exposed to 180 °C, while the components in the paint shop are exposed to lower temperatures of 80 to 160 °C, followed by trim shop and repair areas where ambient temperatures are present. BETAMATE™ and BETAFORCE™ adhesives are also tailored for structural versus hang-on parts and closures.

New BETAMATE™ adhesives, developed exclusively for aluminum applications, provide excellent adhesion to pretreated aluminum, superior stress durability, process stability, and resistance to degradation and corrosion that comes with environmental aging. OEMs are using these adhesives for weight reduction and improved manufacturing efficiencies
in vehicles currently in production.

Temperature-resistant adhesives

The new-generation adhesives display excellent temperature resistance up to 60 °C. They can therefore be stored and processed for very long periods of time. The viscosity increase over time is extremely low and enables a shelf life up to 12 months. *Figure 4* illustrates the viscosity increase over time as a function of the storage temperature.

Optimized rheology for optimal adhesion, squeezability and gap filling

The rheology for new-generation CDAs has been further optimized to processing requirements. The new-generation adhesives are shear-rate dependent, displaying lower viscosity at higher shear rates and higher viscosity at lower shear rates. This has positive effects on the initial tack to oily metal substrates as well as on the adhesive's pumping characteristics, its squeezability and gap filling capability. The latter results in good gap-bridging and geometric stability of the adhesive bead.

3.3 Highly flexible epoxy adhesives for hybrid bonding

Many closures are bonded with low-modulus rubber-based adhesives that exhibit various disadvantages over epoxy adhesive systems. The static and dynamic strengths are significantly lower than epoxy adhesives, and they are generally less corrosion resistant. The glass-transition temperature is situated within the operating temperature range of the vehicle.

The generally higher E modulus of epoxy resin-based structural adhesives can result in read-through effects when bonding exterior panels. A low-modulus adhesive can prevent such issues. Read through becomes an even greater issue because sheet thicknesses have continuously decreased over recent years.

A very flexible epoxy resin adhesive with low modulus has been developed for this application. It possesses significantly higher static and dynamic characteristics than rubber-based adhesives. The dynamic characteristics even match the levels of the crash-resistant structural adhesives. The new adhesive technology unites sealing and reinforcing characteristics in a single product.

Table 3 summarizes the characteristics of old and new structural adhesives. The E modulus is significantly lower and the elongation at break clearly better. The values for the mechanical characteristics are equal or slightly lower. In total, the performance level is significantly greater compared to rubber-based adhesives.

	New-generation CDA	Former-generation adhesive
E modulus (MPa), ca.	400	1600
Elongation at break (%), ca.	40	13
Impact peel strength (N/mm)	48	46
Edge shear strength (MPa)	15.4	19.6

Table 3 - Performance comparison between the flexible and a traditional structural adhesive.

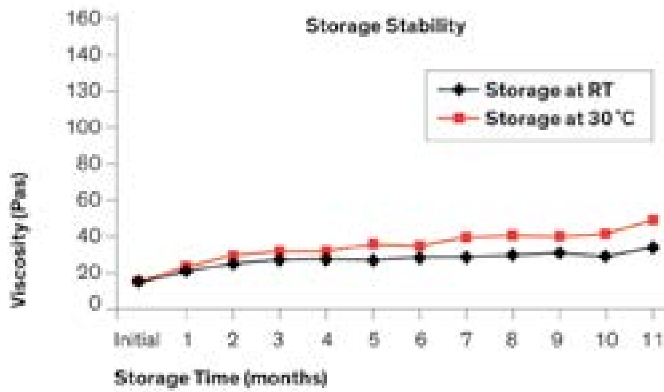


Figure 4 - Viscosity increase over time.

4 Trends in structural bonding of composite materials and coated metal substrates

4.1 Demands on bonding systems for composite materials

The motivation factors detailed earlier for reducing vehicle weight have also resulted in a closer consideration of composite materials as a lightweight solution for traditional metal applications. Roofs, hoods, rear lids, and exterior claddings of future hybrid and electric vehicles will provide particular growth potential for the use of composite materials. Applications are the same for electric vehicle weight reduction since they can weigh 200 to 300 kg more due to construction- and component-related requirements.

In order to insure optimal use of new lightweight materials, innovative adhesive technologies capable of creating stable structures and withstanding high static and dynamic loads under various driving conditions are necessary. The integration of composite materials and plastic bonding in vehicle production processes requires systems with very short hardening times. Simultaneously, less temperature-dependant strength and stiffness behaviors are necessary since the traditionally applied two-component PU systems possess a glass-transition temperature within the vehicle operating range. High-performance structural bonds must be able to accommodate varying part tolerances when joining dissimilar materials and with differing joint geometries.

4.2 New generation of “temperature-independent” high-performance PU adhesives

New primerless adhesives have been developed as a credible alternative to traditional bonding technologies for composite materials. These systems allow bonding of various materials such as sheet-molding compound or carbon fiber-reinforced plastics to coated metal substrates (steel or aluminum). This new generation of adhesive systems provides developers and design engineers new opportunities:

- Increased stability of modulus and strength values across a broad temperature range (-45 to 180 °C)
- A high level of strength and elongation, independent of the bond thickness
- Improved aging performance
- Significantly lower bonding times through optimized curing behavior – with cycle times of less than 60 seconds.

Newly developed PU adhesives provide outstanding shear strength at high temperatures. The chart in *Figure 5* directly compares a traditional PU adhesive with a newly developed PU adhesive.

The chart in *Figure 6* illustrates the exceptionally high shear strength of newly developed PU adhesives with simultaneous high elongation.

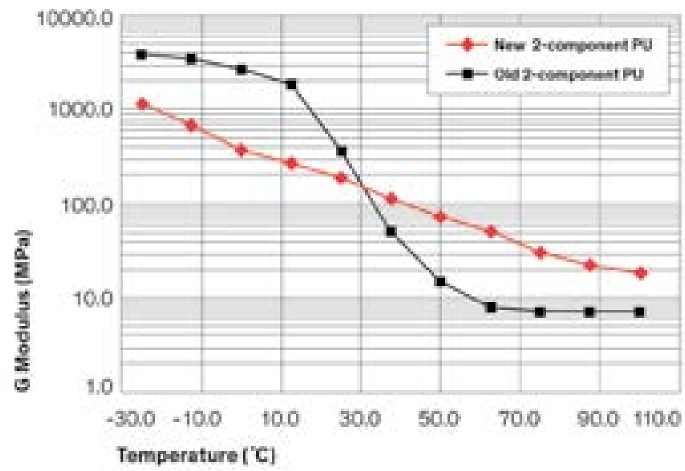


Figure 5 - Modulus over temperature for existing and new structural PU adhesives.

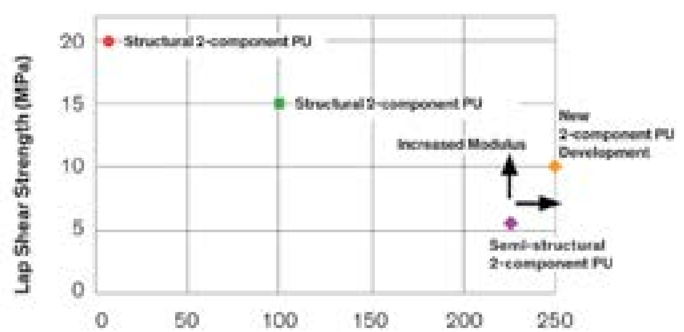


Figure 6 - Strength and elongation properties of structural PU adhesives.

5 Reinforcement foams for body cavities

For several years, vehicle engineers have been able to use reinforcement solutions from thermoplastic and thermoset materials during body development. The structural foams presented here are two-component PU-based reinforcement materials. They are applied directly in body cavities on the production line in order to avoid unwanted dents and buckles in certain areas. Immediately following application, the expanded foams harden inside the cavity. Depending on the foam system, hardening will be completed after only a few seconds. The foam densities vary in structure-relevant applications, ranging from 200 to 600 g/l. Usually structural foams are applied to surfaces which are already corrosion-protected in order to achieve the greatest possible adhesion between foam and surrounding structure.

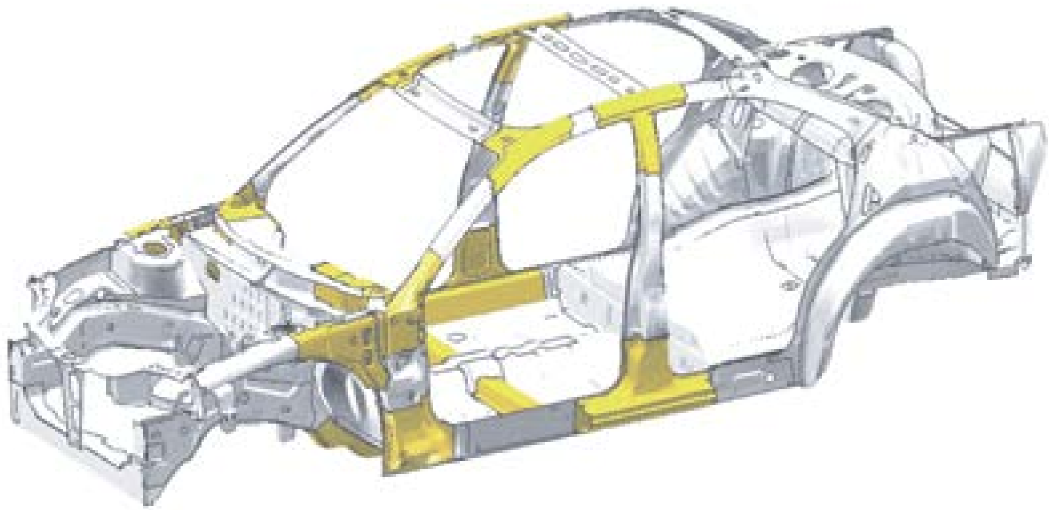


Figure 7 Structural foam applications to the vehicle body.

PU foams provide the additional advantage of very quick processability while allowing the targeted adjustment of the structural performance of a body platform. Traditional metal reinforcements can often be replaced in a weight- and cost-optimized manner. Such systems can also quickly and easily be adjusted to new requirements, such as design changes. A development engineer can directly fine-tune characteristics such as body stiffness, crash performance, and acoustic performance via foam density and injection volume.

We can summarize foam performance characteristics as follows:
- Increase crash performance and stiffness levels while reducing weight
- Lower system costs due to local reinforcement driven by low material cost
- Design freedom with no costly tools required since foams are applied directly to body cavities
- Scalability to meet targeted configuration demands and performance requirements – a single lean platform allows formation of different structural derivates by varying foam density and injection volume

6 Summary

Epoxy resin and PU structural adhesives have become indispensable components of modern car construction. Originally, such materials served to increase crash performance and long-term durability. From a current perspective however, lightweight body construction has become a primary consideration. This includes the substrate mix, i.e. the combination of various metallic and non-metallic materials where structural adhesives are used for many different applications. The continuous development of bonding systems will ensure that novel substrates can be bonded with optimized safety and durability in the future as well.

Locally effective structural foams complement the lightweight construction potential of such adhesives and furthermore provide substantial advantages with regard to flexible design and manufacturing of different vehicle variations. Unwanted bending and buckling behavior in the vehicle structure can be prevented in a targeted manner. Load paths can thus be effectively optimized.

Though natural resource shortages and environmental protection were initial societal and legislative drivers of lightweight design, consumer behavior and fuel prices continue to increase demand for it.

Epoxy resin and PU structural adhesives provide wide-ranging benefits apart from weight reduction that are relevant to consumers. Safety improvement, noise reduction and other gains will continue to increase their use in future vehicle designs.

About DuPont Transportation & Industrial

DuPont Transportation & Industrial (T&I) delivers a broad range of technology-based products and solutions to the transportation, electronics, healthcare, industrial and consumer markets. T&I partners with customers to drive innovation by utilizing its expertise and knowledge in polymer and materials science. T&I works with customers throughout the value chain to enable material systems solutions for demanding applications and environments. For additional information about DuPont Transportation & Industrial, visit dupont.com.

dupont.com

Transportation & Industrial

Form No. 001-20033-HMC419