FACTORS ESSENTIAL FOR ADHESIVELY BONDED COMPOSITE JOINT DESIGN IN AUTOMOTIVE APPLICATIONS

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Abstract
Adhesive bonding is widely established in automotive applications for improving stiffness and performance of steel members under impact (crash) loading in body-in-white applications.
In contrary to aerospace and general industrial applications, joints involving composite materials in automotive applications are restricted in design and space available for effective substrate stiffness alignment (e.g using scarf or stepped design). Effective joint design is therefore mainly driven by the use of suitable adhesive materials, bondline thickness and layup conditions. The paper addresses the major parameters and their impact to joint performance and substrate integrity. The development of flexibilized adhesive grades with lower modulus (however appropriate to meet the stiffness requirements of actual passenger car design) enables composite joints with sufficient shear strength to be realized, preventing the substrates from failure or delamination.

1. Introduction

Adhesive bonding is widely used in automotive applications for improving stiffness and performance of steel members under fatigue or impact (crash) loading conditions in body-in-white and chassis applications. It has been initially introduced as backup technology to spot welding, or other jointing techniques with the ability to be integrated in fully-automated industrial manufacturing processes.

Adhesive bonding gains now considerable attention as primary assembly technology due to the lightweight trends and the use of dissimilar materials than cannot be effectively jointed using mechanical fastening or welding techniques. For parts made using fiber reinforced plastic (FRP) materials, adhesive bonding is the most effective assembly technique due to its ability to transmit loads relatively evenly and to avoid high stress concentrations. In absence of mechanical fasteners, the substrate stays unaffected.

Although the use of fiber reinforced plastics is a very attractive option, the most likely scenario for cost-effective lightweight design in near future is the use of a variety of materials (Fig. 1) such as advanced and ultra-high strength steels, aluminium or magnesium alloys, composites and engineering plastics as appropriate [1], corresponding to the particular weight target and the functional or strength requirements of each actual part or parts group. Also, hybrid parts may be relevant consisting of both, metal and FRP materials taking advantage of their respective strengths.

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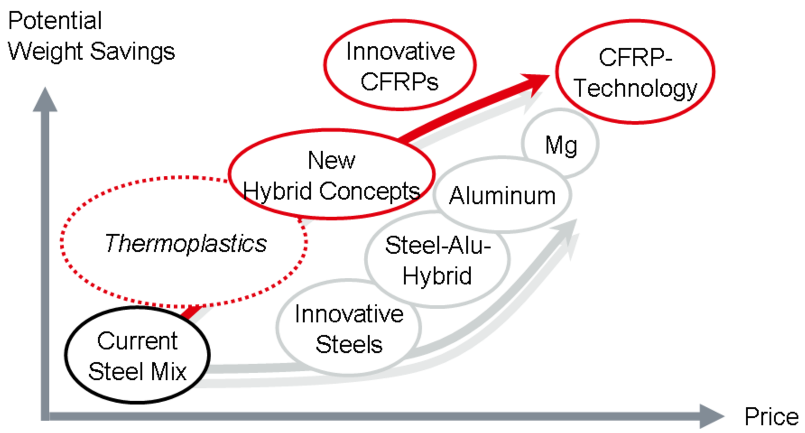

Figure 1. Lightweight material trends

Successfully integrating composites into commercial vehicles that are produced in mass requires significant modifications in many of the design and analysis practices in the automotive industry. In contrary, design and process constraints may affect the use of composites in mass automotive applications. Fast manufacturing processes such as resin transferred moulding (RTM) are most likely to establish in series production. Manufacturing of hybrid structures in a single production step is with the current RTM process variants not possible [2] therefore bonding of multi-material parts is required.

Some of the suggestions widely used for joint design in aerospace applications cannot be transferred to mass production vehicle design. Also, the integration of composite parts can take place at different manufacturing process stages. This may affect the selection of the adhesive system to be used.

2. Process issues

Adhesives for use to bond parts in multi material design must exhibit sufficient adhesion to dissimilar materials such as CFRP, e-coated steel, aluminium or other lightweight metal alloys. Adhesion to composite material is predominantly driven by polarity of the matrix resin, surface energy and wettability (Fig. 2). The performance of the bond may also be affected by the surface micro structure. However, surface micro texturing additional to standard abrading operations is currently unusual.

A major challenge is good adhesion ability to composite surface without extensive pre-treatment. Thermoset composites are easier to adhesively bond than thermoplastic ones as they exhibit higher surface wettability. Surface preparation remains however standard requirement in actual manufacturing processes including an abrading operation after standard cleaning. This is mainly attributed to the presence of mold release chemicals on the surfaces used to facilitate part production, or potentially incorporated as internal release agents.
Thermoplastic and in general composites with insufficient surface wettability usually require surface activation that can be a flame, corona, or a plasma treatment, or use of appropriate primer.

Adhesive products and mold release agents can be adjusted to each other providing sufficient adhesion and thus, eliminating the need for removing the later from the composite surface prior to bonding. Proprietary composite technologies and adhesive systems aligned to the entire FRP production chain have therefore distinct appeal to composite design engineers.
The Henkel corporation has developed polyurethane resins for high pressure Resin Transfer Molding processes with considerable toughness properties and fatigue performance that facilitate mass production, and offers comprehensive portfolio of adhesive products that are adjusted to the matrix chemistry and internal mold release agents used for process efficiency.

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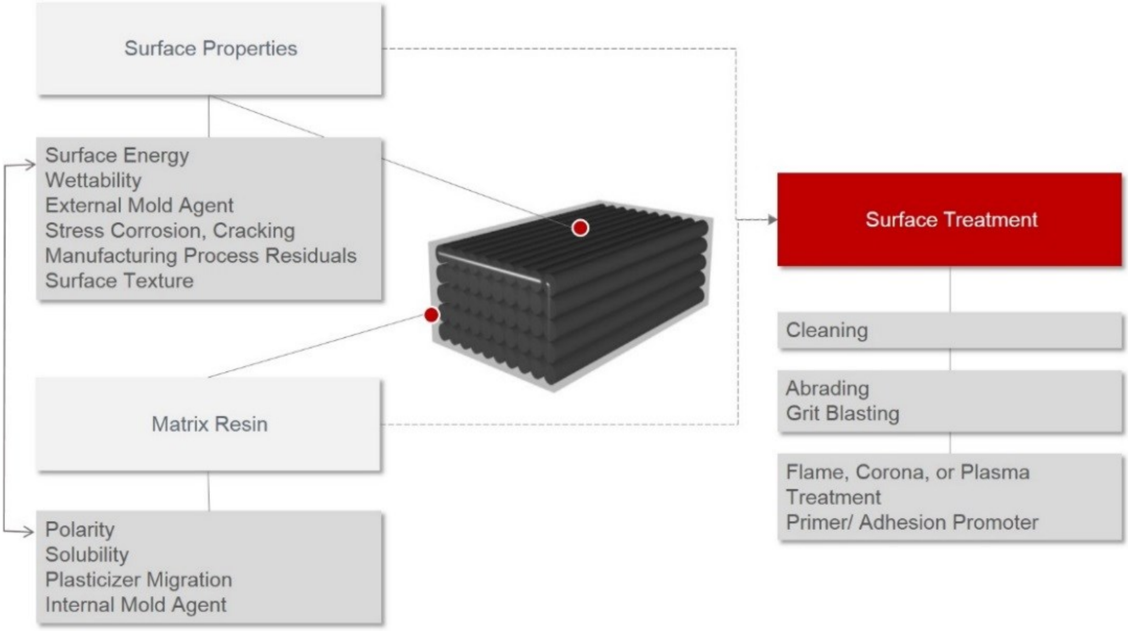

Figure 2. Factors affecting adhesion ability to composite surfaces

The thermal sensitivity of composites may drive the bonding process into the assembly line, preventing the materials from heating in standard oven processes. The issue however is still controversial since the automotive industry is reluctant to revise established manufacturing processes when moving towards multi-substrate design incrementally.

Depending on the process step selected for composite part integration, different adhesive technologies may be considered. The main differentiating factor is the ability of the adhesive system to cure practically at room temperature (or by limited heat supply), respectively to cure making use of the paint/e-coat oven thermal cycle conditions (Fig. 3).

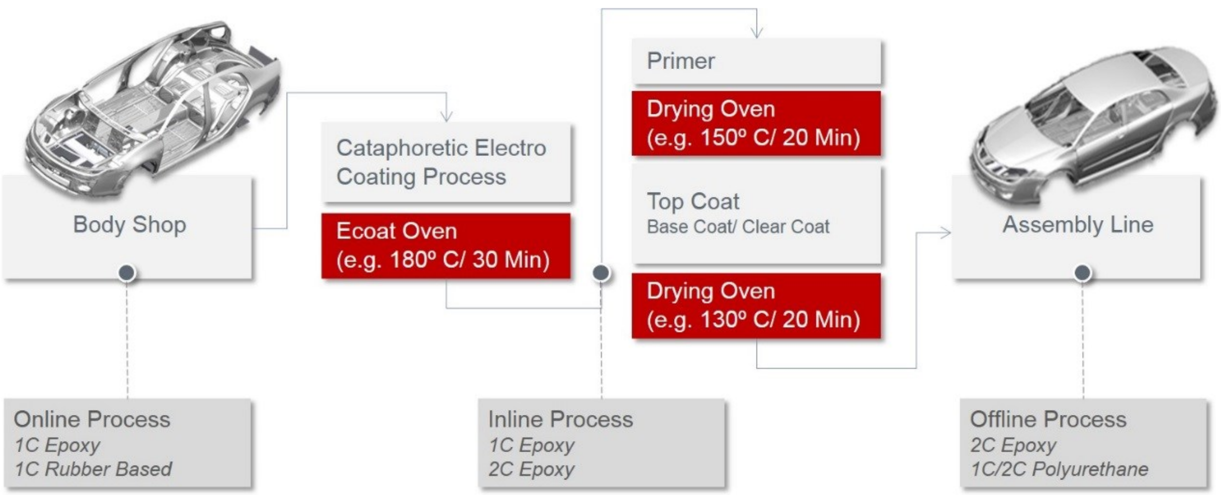

Figure 3. Integration of bonding processes in automotive production workflow

3. Design parameters

Adhesive bonding enables in general loads to be transmitted evenly, avoiding high local stress concentrations or section weakening. However, load transfer leads by nature to differential straining of

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the joint parents at the overlap ends and therefore to higher local shear stresses than the nominal (average) one. These stress peaks may be affected by deviating substrate stiffness or thermal expansion properties when thermal loading is considered.

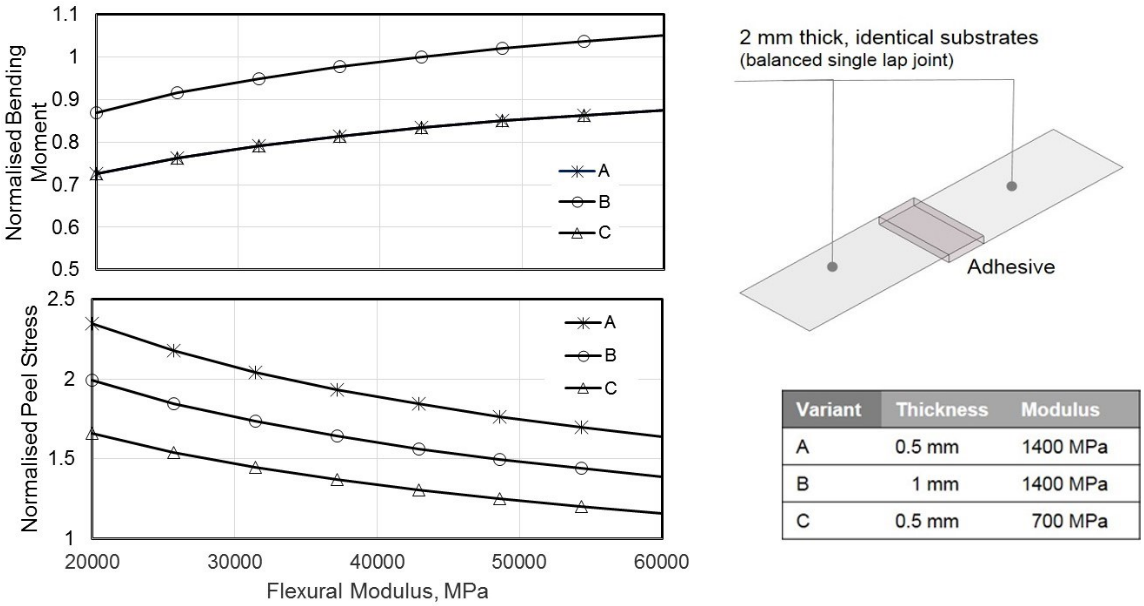
Load path eccentricity results also to bending stresses additional to the membrane ones, and thus to peel stresses perpendicular to the interface.

Overlap end stresses may be accommodated by appropriate, gradual or incremental adjustment of the adherend stiffness. This implies suitable tapering of the adherends at the ends of the overlap or use of stepped lap joints when adherend thickness is sufficient [3]. Inner (or reverse) tapering allows for additional stress reduction as it results in local thickening the adhesive layer at overlap ends [4]. Scarf joints may be realised by tapering metal adherends, while the tapering of the FRP members usually takes place by appropriate ply drop-off. These design options have been proposed for aerospace applications, and their application is reasonable for adherends with sufficient thickness and joints with large overlap lengths.

In contrary to aerospace or wind energy applications, joints involving composite materials in automotive structures are restricted in design and space available for successful substrate stiffness alignment. Effective joint design is therefore mainly driven by the use of suitable adhesive materials, bondline thickness and adherend stiffness properties.

3.1 Bond line properties

Overlap end stresses in a lap joint are affected by the compliance, i.e. the modulus of elasticity and in general the deformation ability, and the thickness of the adhesive bond. The drop in stresses turns from local to global and thus appears very pronounced when differential thermal expansion has to be accommodated.



Variant	Thickness	Modulus
A	0.5 mm	1400 MPa
B	1 mm	1400 MPa
C	0.5 mm	700 MPa

Figure 4. Bending moment conditions in single lap shear adherend, and maximum peel stress as function of the flexural modulus of the composite substrate. Bending moment and maximum peel stress are normalised with respect to a reference joint with steel substrates of identical thickness.

Figure 4 demonstrates the reduction in peel stress by increasing the thickness of the adhesive layer respectively decreasing the elasticity modulus of the adhesive grade used in a standard structural lap

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joint. Bending moment and maximum peel stress are normalised with respect to a reference joint with steel substrates of identical thickness. Estimation of the bending moment conditions and the maximum peel stress are based upon the approach proposed by Hart-Smith [7], s. also VDI 2014 [8]. Bond line thickening allows the peel stress to decrease, however the bending moment increases due to the load path eccentricity and may lead therefore to higher substrate loading. By the use of an adhesive that is more compliant than the structural adhesive initially suggested, a stronger reduction of the peel stress can be achieved without an increase in bending moment conditions. Thus, the use of compliant adhesives is an effective way to limit the peel stress generated in the overlap.

Reduction in adhesive grade stiffness however may be associated to loss in strength properties, depending on the polymer chemistry used or the particular modifications applied. In contrary, increasing the bond line thickness has positive impact to the joint performance for most structural and semi-structural adhesive grades. For epoxy-based structural adhesives, increase of fracture toughness in tensile separation mode by the adhesive layer thickness appears to some degree attributed to the constrain effects of the plastic zone at small bond line thicknesses [5].

3.2 Laminate properties

Overlap end stresses in an adhesively bonded joint are affected by the mechanical properties of the substrates. Shear stresses in the longitudinal direction result at the overlap ends from differential extension between the fully loaded substrate and the opposite one gradually subjected to straining as the load transfer progresses. The overlap shear stresses depend therefore on the extensional and coupling stiffness of the laminate (assuming the laminate however to be symmetric, the components of the coupling matrix B vanish), but also on its bending stiffness.
Peel stresses at the overlap ends are strongly affected by the flexural stiffness properties of the substrate material (s. also Figure 4).

For symmetric laminates, irrespectively of being balanced or not, the matrix coefficients D_{16} resp. D_{26} are not inevitably zero. Coupling effects may therefore lead to non-zero shear stresses along the width, usually being of minor magnitude, and to considerable out-of-plane peel stresses, as bending implies additional twisting [6].

3.3 Composite part integrity

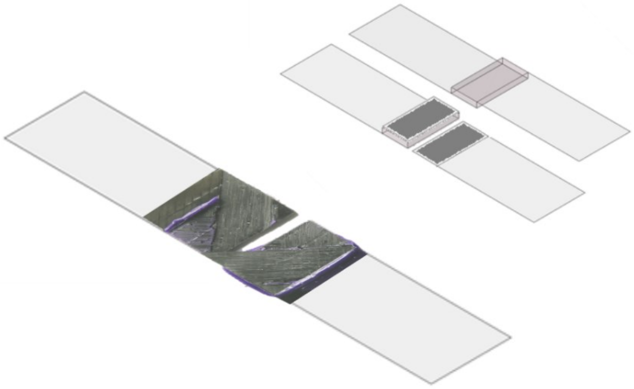

Figure 5. Fracture surface in ±45° laminate used in lap shear testing. Bonded joint realized using high strength structural adhesive.

Although the design of the composite bonded joints is intended to provide maximum bond line performance, failure may also occur in the composite adherends. Depending on the layup and the

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loading conditions, a section fracture of the surface ply may be often observed associated to interlaminar or intraply delamination and finally to complete fracture of the remaining section.

In thin composite adherends, fracture of the filament close to the adhesive joint usually initiates an interlaminar shear failure within the laminate (Figure 5). For thicker adherends, the dominant failure modes are peel tensile stresses in the adhesive and the associated interlaminar tension stresses in the composite adherends [3,4,7].

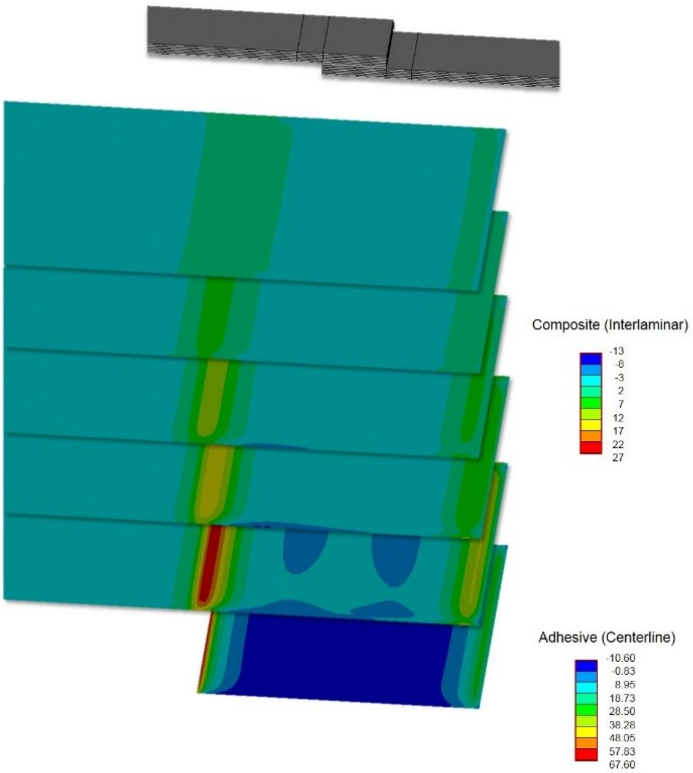

Figure 6. Peel (through-thickness) stresses in adhesive bond line and quasi-isotropic [0°/-60°/60°]s composite substrate of a lap shear test joint. Stresses evaluated in the centerline of the adhesive resp. at single ply interfaces.

The high peel stress near the overlap end and the weak interlaminar strength are believed to be one of the major factors driving delamination along the interface between the surface and the second ply in a composite adherend. Through-thickness peel stresses however continuously decrease with the distance from the interface (Figure 6). For their treatment using numerical methods it may be probably sufficient to model the surface ply and its interface to the second one by means of separate element representation.

3.4 Adhesive selection

The selection of a suitable adhesive for mass production vehicle design depends on the process constraints and the curing technology appropriate for the desired production step. Toughened high-strength structural adhesives designed for bonding crash-relevant members are likely to withstand higher loads than thin composite members are able to do without to fail. Although ductile in comparison to standard epoxy-based structural adhesives, they exhibit considerable stiffness leading to peel stresses under axial loading and thus, tend to initiate delamination or filament failure in surface ply.

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Toward an effective peel and overlap end stress reduction by the use of flexibilized or low modulus adhesives, the stiffness requirements of the actual car passenger design shall remain fulfilled. A computational study [9] indicated 15% loss in torsional stiffness when using a windshield adhesive for bonding a CFRP-roof onto a conventional steel car body. Parametric studies on a CFRP roof substitute manufactured using MAX2 PU resin (Figure 7) indicate minimum reduction of the torsional stiffness (<1%) when using an adhesive grade with a modulus of elasticity in the area of 0.3 GPa.

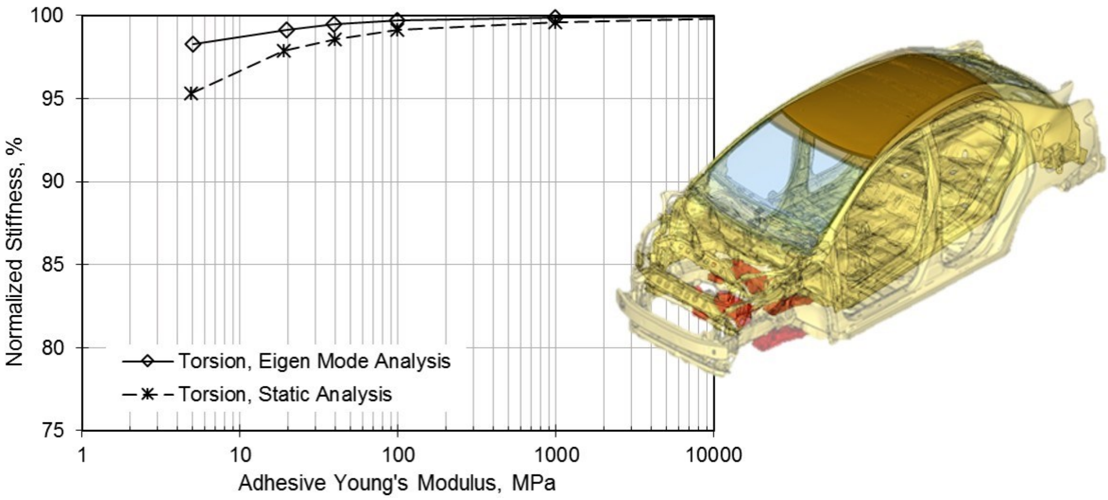

Figure 7. Torsional stiffness of a car structure with CFRP roof substitute using adhesive grade variable in stiffness. Values normalized with respect to a virtual adhesive with elasticity modulus equal to steel. Static analysis by force couple acting on wheel suspension points.

1-component structural adhesives for use in body shop (to be cured by heat during a typical ecoat oven temperature cycle) can be flexibilized as hybrid epoxy-urethane systems or by selection of appropriate pre-polymers. The use of structural adhesives with high elasticity modulus leads to high strength values associated however with substrate failure (Figure 8).

Polyurethane-based adhesives can be cured at room temperature (2-component) or by short low-temperature cure when designed as fast 1-component systems. Recently developed grades with a moderate Young's modulus (≥300 MPa) fulfil the stiffness requirements in car passenger design. They also prevent composite substrates to fail for typical layup conditions until sufficient shear strengths have been achieved and enable efficient bonding solutions in the assembly line.

Adhesive Grade	Process	Modulus (MPa)	Strain at Break	Substrate	Shear Strength (MPa)	Failure Mode
Epoxy	1C/ 30 Min @180°C	1560	<5%	CFRP ±45°	20	Composite failure
Epoxy	2C/RT	1250	25%	CFRP [±45°(0°/90°)2]s / E-coated Steel	≥ 18	E-coat failure
Polyurethane	1C/ 30 sec @80°C	75	120%	CFRP ±45°	12.8	Cohesive
Polyurethane	2C/RT	340	100%	CFRP [±45° (0°/90°)2]s / E-coated Steel	≥ 15.5	Cohesive

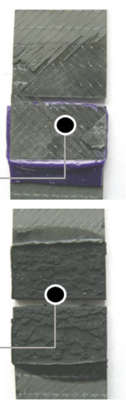

Figure 8. Adhesive products for composite substrate bonding. Typical stiffness and strength properties corresponding to failure modes observed in lap shear testing.

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4. Summary

Adhesive bonding is widely established in automotive applications for improving stiffness and performance of steel members under impact (crash) loading in body-in-white applications. For parts made using fiber reinforced plastic materials, adhesive bonding is the most effective assembly technique due to its ability to transmit loads relatively evenly and to avoid high stress concentrations. However, load path eccentricity leads to additional bending moment in the adherends at the ends of the overlap, and thus to significant peel stresses.

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