Joining & Bonding of Composite Parts – The Structural Adhesive Advantage

Recent trends and advancements in the manufacturing and cost reduction of composite materials has increased their usage in the transportation, industrial, and many other markets in addition to their traditional use in the aerospace field. Driven by increased government regulations on vehicle emissions, the need for light weighting, and increased end consumer demand for higher performance products, composite materials and parts are increasingly becoming part of an engineer's day to day design specification. Composites are used in a wide variety of applications to reduce weight, provide improved environmental resistance, improved aesthetics, greater design options and increased stiffness to weight ratio.

Composite materials, for the purpose of this paper, focus on polymer matrix composites – fiber-reinforced plastics, both thermosets and thermoplastics. Working with these composite materials brings the challenge of how to join composite parts, to themselves and to multiple materials such as steel or aluminum. This paper discusses the features and benefits of structural adhesives for bonding composite parts, the advantages of adhesives vs. mechanical fastening specific to composite materials, the type of assemblies and applications typical for composite materials, how to select the appropriate adhesive to maximize your product, part, or joint, and testing and prototyping for bonding of composite parts.

Advantages of Adhesives for Composite Bonding

Composites require new methods of bonding or joining (beyond traditional mechanical and thermal methods) to allow for design and performance optimization. Fortunately, advances in structural adhesives (such as epoxies, acrylics, and urethanes) have enabled designers to create products meeting structural integrity requirements without the use of mechanical fasteners, rivets, or welding. Additionally, these structural adhesives work well with multiple substrates including plastics, metals, and composites without sacrificing performance properties. Even Low Surface Energy (LSE) plastics, such as thermoplastic polyolefin (TPO), polypropylene (PP), and polyethylene (e.g. HDPE), which in the past had to be mechanically attached or heat welded, can now be bonded with specialty structural adhesives.

To join composites or mixed materials, mechanical attachments (such as clips, screws, etc.) can be used with virtually any surface, but they require additional steps to mold or create features for the attachment. This can lead to stress concentrations, which may result in plastic cracking and premature failures. Also, drilling holes into composite materials will result in reduced strength due to the introduction of discontinuities in the matrix and reinforcing fibers. All mechanical attachment methods will result in increased weight and often poorer aesthetic finish. Heat and friction welding is a common alternative for certain composites. However, these welding techniques are energy and tooling-intensive and limited in the geometries and substrate combinations that can be addressed.

In addition to forming strong bonds, structural adhesives can lower overall costs while increasing the durability of products; and are typically lighter weight than mechanical fasteners. Durability is improved because adhesives distribute stress across the entire bonded area, whereas mechanical fasteners, rivets, and spot welding can create stress concentrations leading to weak points across the substrates.

Furthermore, the use of adhesives provides a way to seal the entire bonding area while also providing a high strength joint. Another huge consideration and advantage for adhesive bonding is the ease in which it allows different materials to be combined – compared to conventional mechanical methods. For example, structural adhesives prevent galvanic corrosion between dissimilar metals. Finally, the cleaner look of bonded joints versus mechanical fasteners allows for better looking, more efficient product builds without additional finishing work. Thus, adhesive bonding could be the best option for joining the next generation of engineering composites and plastics.

Lightweighting

Lightweighting is a mega-trend across many industries. Reducing component weight has great benefits, ranging from improved product design/performance and a decreased end-user cost to less environmental impact. In the transportation industry, the trend towards light weighting is of utmost importance due in part to new governmental regulations and industry pressure to increase fuel efficiencies. Figure 1 below demonstrates the clear trend of using an increased variety of different materials in the construction of future products to reduce weight and improve product functionality.

Lightweighting will often involve a change in design and materials with an increasing number of lighter-weight options available, including various composite materials. Structural adhesives are an enabling technology for these new designs.

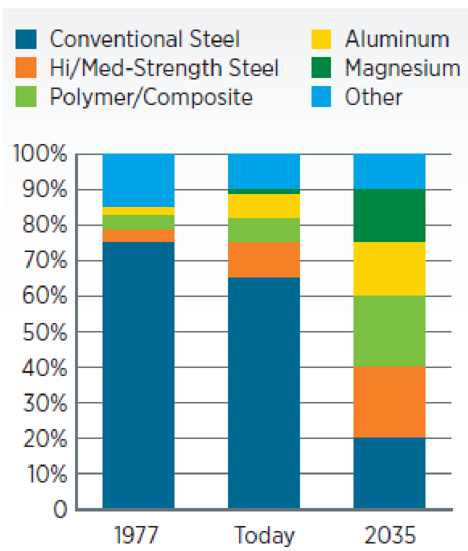


Figure 1. Typical composition of an automobile – material trends (from the US Department of Energy, 2010)

Composites substrates are generally sub-divided into two categories:

a) *thermoset composites:* Glass-filled polyester resins, such as sheet molding compound (SMC), and higher performance carbon fiber-reinforced epoxy resins which can be defined as having a permanently molded shape often involving a lay-up assembly process of reinforcing materials and resins followed by heat and pressure curing in a press or autoclave.

b) *thermoplastic composites:* Glass-filled polyethylene, polypropylene, nylons etc., which can be shaped into fairly complex parts using conventional plastic molding techniques such as injection molding from raw material in pellet form.

These lighter-weight, polymer-based materials are better suited to fabrication and assembly by adhesive bonding rather than traditional mechanical fixings, both from a weight savings and mechanical performance perspective.

Adhesive Bonding of Composites - Illustrative Applications

i) Figure 3 demonstrates the attachment of ABS inserts adhesively bonded to glass-filled polypropylene bumpers using 3M™ Scotch-Weld™ Structural Plastic Adhesive DP8010 Blue. This was the only solution that could provide good adhesion and a permanent structural bond to both surfaces without pretreatment – with the desired aesthetic. 3M™ Scotch-Weld™ Structural Plastic Adhesive DP8010NS Blue has also proven to be very durable in external applications.

Figure 3 ABS to glass-filled polypropylene using 3M™ Scotch-Weld™ Structural Adhesive

ii) Bonding interior trim panels of vehicles. The use of lighter weight thermoplastic composites for the creation of large, lightweight molded interior panels that provide structural support for interior trim is an established trend. Figure 4 shows the application of 3M™ Scotch-Weld™ Structural Plastic Adhesive DP8010NS Blue adhesive to a thermoplastic bulk head part which is being bonded to an aluminum frame.

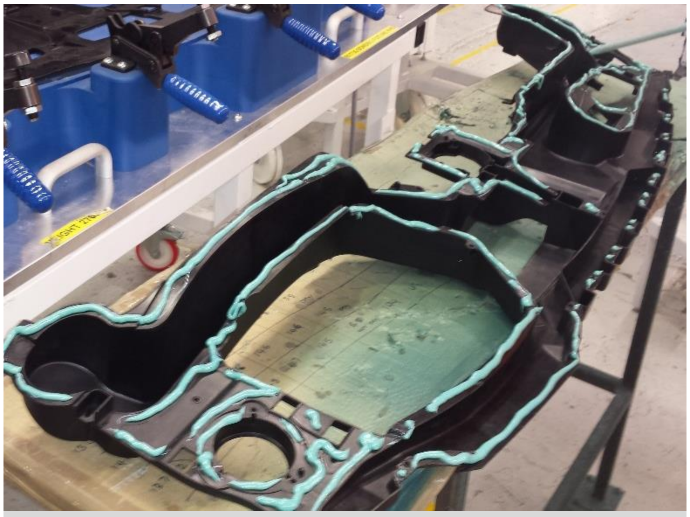


Figure 4. Lightweight glass-filled polyolefin bulk head moulding – being bonded with 3M™ Scotch-Weld™ Structural Plastic Adhesive DP8010NS Blue to an aluminum frame

iii) Specialty vehicle manufacturing (commercial bus and coach in this case) can utilize a number of different bonding options. Figure 5 shows a 3M polyurethane adhesive sealant being used to bond the glass-reinforced plastic (GRP) side panel to a coated steel frame. The 3M adhesive sealant was able to withstand the loads applied to the panel during use and also accommodate the necessary movement created by the vibrations and differential thermal expansion. An interesting feature of this application was that the customer was also using a small amount of 3M™ VHB™ Acrylic Foam Tape in combination with the adhesive sealant to provide a fast time to handling strength and speed up production.

Figure 5. GRP panel bonding to steel using a 3M™ Adhesive Sealant

iv) Composite materials are finding increased use in oil exploration and marine applications. Reducing weight on drilling platforms allows more oil to be pumped and stored on the platform. It also allows for easier equipment transportation and installation in environments with difficult access. New evolutionary lightweight shale shaker designs, containing a significant amount of carbon fiber composite, have been developed using a toughened and high performance 3M™ Scotch-Weld™ Structural Epoxy Adhesive DP490 for the assembly solution. These bonded joints (both carbon fiber to carbon fiber and stainless steel to carbon fiber) have been thoroughly field tested and shown to be durable as they can resist dynamic loading (shakers/filters vibrate several hundred times a minute and pull up to 7g of load). They are also resistant to the crude oil / hydrocarbon “mud” /fragments of rock mixture flowing at around 80 to 100°C.

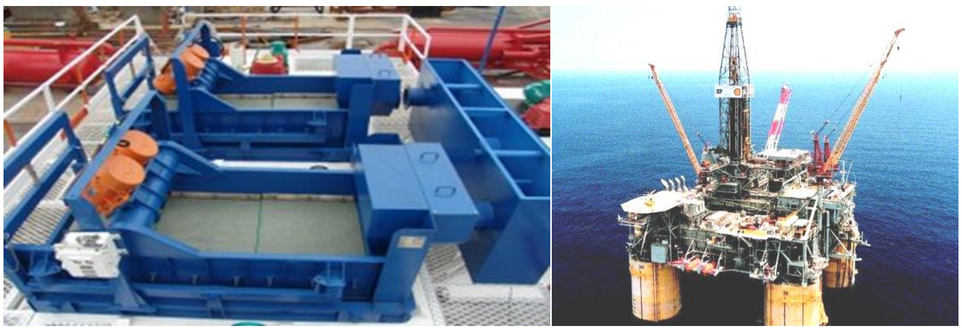


Figure 6. Carbon fiber composite panels bonded to stainless steel for lightweight oil shakers using a 3M™ Scotch-Weld™ Toughened Epoxy Adhesive.

v) Syntactic foam composites containing 3M glass bubbles find extensive use in marine applications helping to reduce the density, increase buoyancy, and reduce overall weight. 3M™ Scotch-Weld™ Epoxy Adhesive 2216 and 3M™ Scotch-Weld™ Structural Plastic Adhesive DP8010NS Blue (for syntactic foams based on Polyolefins) have proven durable and reliable even in applications submerged under sea water.

Figure 7. Syntactic foam buoyancy aid bonding to aluminum using a 3M™ Scotch-Weld™ Epoxy Adhesive 2216

Maximizing Performance with Joint Design and Adhesive Selection

The importance of choosing an Adhesive with appropriate physical properties for the design.

Particularly for fiber-reinforced materials, the durability of the joint is determined by the capability of the adhesive to evenly distribute the load to the upper matrix of the composite to prevent premature failure due to stress-localization; and furthermore the performance of the joint will depend upon the modulus of the substrates as well as that of the adhesive. In all cases, however, it is important that the actual stresses in the joint remain below the capability of the adhesive, with an appropriate safety factor applied. Because the relative modulus of the substrate and the adhesive are so critical in composite bonding, as well as the elongation of the adhesive (discussed below) it is critical to consider some basic properties of the adhesive when selecting a set of products to test.

The stress-strain curve is critical to understanding the physical properties of the adhesive, and how it responds to stress. When a load is applied, the polymer (adhesive) will generally first respond elastically and the stress will increase with a constant rate. At a certain point, the polymeric backbone will no longer be able to take the applied stress and start to deform plastically (with a permanent deformation). Depending on the polymers capability to deform, it will elongate until it finally breaks. The area under the curve represents the energy which the polymer absorbs during this process. The larger this area is, the more energy is needed to make the adhesive sample break.

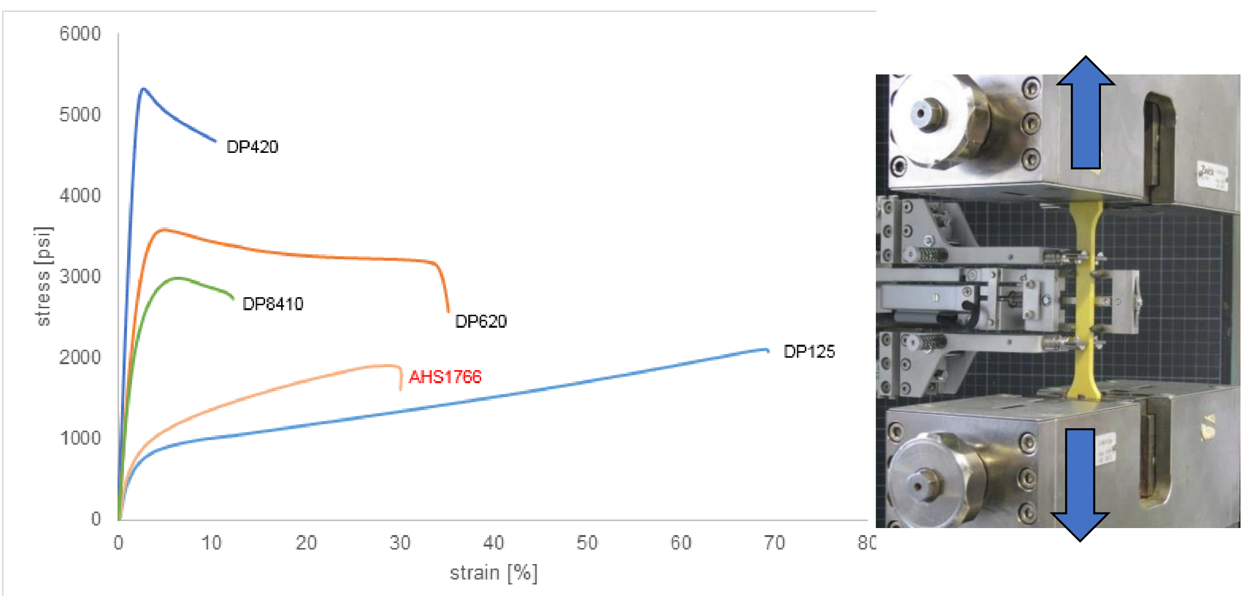


Figure 8: The image above is showing some stress-strain curves of a selection of adhesives. For this, load is applied to a dumbbell-shaped specimen as shown on the right side. The curves represent the different families of adhesives. Toughened epoxy (DP420), toughened polyurethane (DP620), methacrylate (DP8410), flexible Urethane (DP6330NS) and flexible epoxy (DP125)

The lap shear value is a second data point to consider. This value represents the adhesive's adhesion to the substrate surface combined with the cohesive strength of the adhesive as a cured polymer. Adhesion depends upon chemical compatibility between adhesive and substrate, allowing the adhesive to fully wet the substrate's surface and create a chemical bond to it. A general rule would be to balance the capability of wetting a substrate's surface to generate sufficient adhesion (tested by lap shear) with the required amount of cohesive strength to guarantee a capable design (related to stress/strain curves). Whereas the first criteria is strongly bound to the chemical nature of the non-cured adhesive, the latter is a function of the nature and composition of the cured adhesive.

However, lap shear also depends on modulus as well as adhesion to the substrates.

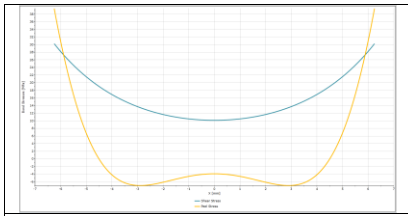
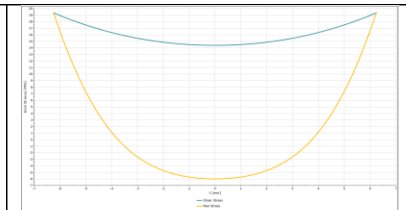
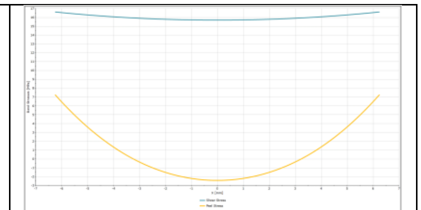
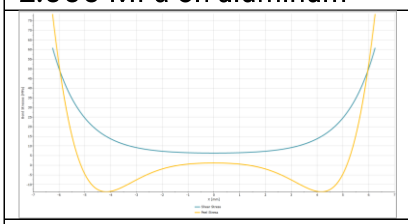
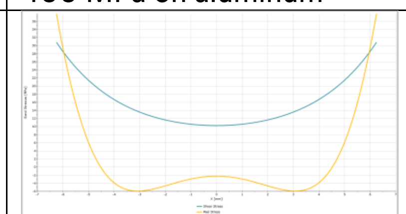
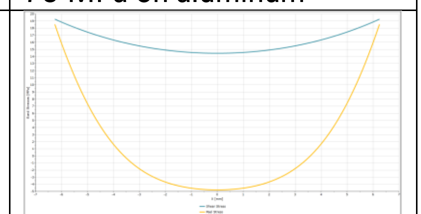
		
Adhesive with a modulus of 2.000 MPa on aluminum	Adhesive with a modulus of 400 MPa on aluminum	Adhesive with a modulus of 70 MPa on aluminum
		
Adhesive with a modulus of 2.000 MPa on composite	Adhesive with a modulus of 400 MPa on composite	Adhesive with a modulus of 70 MPa on composite

Figure 9: closed form calculations of stress within an adhesive joint as a function of modulus of the substrates and adhesive.

The above images (Figure 9) show calculated shear (blue) and peel (yellow) curves over the length of a single lap shear specimen on aluminum (upper images) and fiber-reinforced composite (lower images). Aluminum has a modulus of approximately 70 MPa and the composite (GF-polyester) has a modulus of approximately 10 MPa. The applied load for this calculation was 200 N per mm bond length. The adhesive thickness is 0.3 mm, the substrate thickness 2 mm. It is easily approximated with closed form calculations that for aluminum, a very stiff adhesive (high-strength EP, 2.000 MPa) is a good choice, whereas the same adhesive leads to almost double the peel forces on the composite material. This could be fatal for the joint as the upper matrix layer of the composite is likely to fail and lead to premature breaking. An adhesive with a modulus of about 400 MPa gives a comparable scenario on the composite joint (center image, composite). The same trend can be seen with the 400 MPa adhesive on aluminum and the 70 MPa adhesive on composite. Using those adhesives in these cases would minimize the peel forces at the ends of the joint and lead to a shear-focused load case, which results in a much more durable bondline.

So for a robust joint, the cohesive strength (inner strength of the adhesive) must be high enough to guarantee structural strength of the joint, but the adhesive also needs to evidence a stiffness which is suitable for the substrate material.

Selecting the right adhesive for glass-fiber reinforced polyester

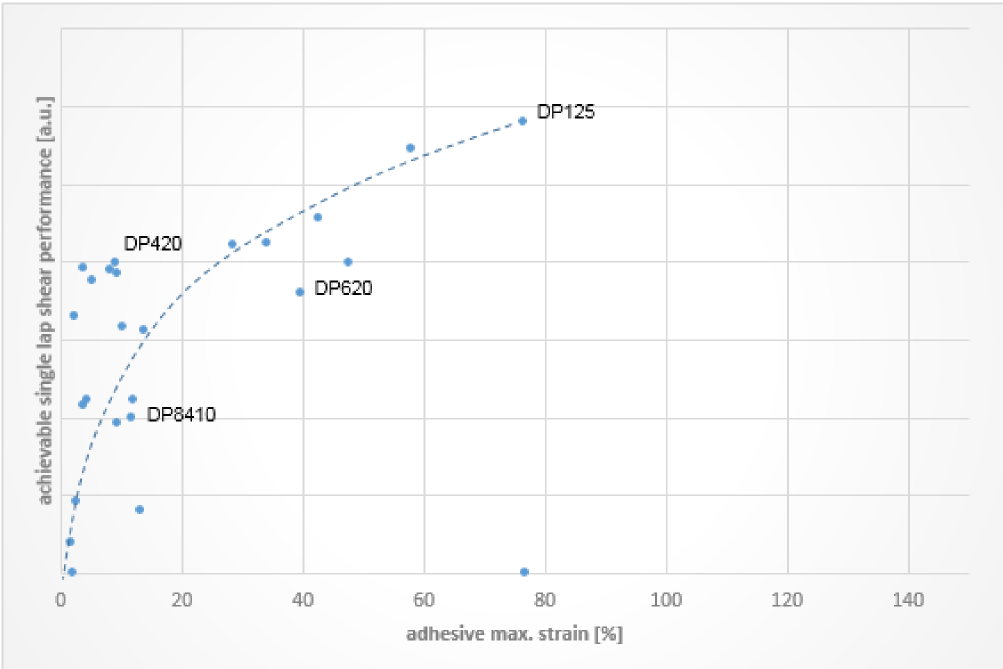


Figure 10: The above image shows the maximum achievable lap shear performance of a selection of adhesives on abraded glass-fiber-reinforced polyester substrates.

Referring to Figure 10 above, the best performing adhesive in this series is 3M™ Scotch-Weld™ Epoxy Adhesive DP125. It has a modulus of about 60 MPa at room temperature, significantly lower than most epoxy adhesives. The important lesson here is that the stiffer (higher modulus) adhesive is not always the best choice, especially when materials other than metals are involved.

When bonding composite parts, it is also important to decide which mode of failure of the joint would be desired. In many cases, and especially for thermoplastic composites, it is desirable to generate a bonded joint which tolerates more load than the substrates themselves. In these cases, the joint fails due to substrate breakage. This is a good way to assure oneself that the adhesive is the superior component and that the joint design was conservative. However, in those cases where the composite parts are extremely expensive, i.e. high-strength carbon fiber-reinforced epoxide parts, it becomes important that – even if the joint fails -- it does so in a cohesive mode within the adhesive layer. This may allow for re-use of the parts after the required inspection and release.

There are three major families of structural adhesives: acrylates (MMA), polyurethanes (PU) and epoxies (EP). In all adhesives families, their products can differ significantly in cure speed, final strength and achievable elongation. Since each of these families differ in their chemical make-up and general physical properties, each of the adhesive families have some desirable properties for certain kinds of substrates or load scenarios. But choosing between and within these three families is the big challenge when looking for the right adhesive for an application.

To be able to provide substantial help to the customers during the design phase of an application, 3M has available a selected go-to portfolio for composite materials to generate a helpful guideline for the selection of adhesives. The necessary physical and thermal property data for these products is available, as well as lap shear strengths.

Composite Application - Bonding needs	Adhesive Properties	3M™ Scotch-Weld™ Structural Adhesives	Link to webpage
General Composite Bonding	Urethane	3M™ Scotch-Weld™ Multi-Material Composite Urethane Adhesive DP6330NS	DP6330NS
General Composite Bonding	Two-part epoxy	3M™ Scotch-Weld™ Epoxy Adhesive DP125 Gray	DP125
High Strength & Durability	Toughened Epoxies	3M™ Scotch-Weld™ Epoxy Adhesive DP420 Black	DP420
Strong bonds with some flexibility	Flexible Epoxies	3M™ Scotch-Weld™ Epoxy Adhesive DP190 Gray	DP190
Flexible bonding	Flexible Urethanes	3M™ Scotch-Weld™ Urethane Adhesive DP620NS Black	DP620NS
Tough, durable, plastic & metals	Acrylics	3M™ Scotch-Weld™ Acrylic Adhesive DP8410NS Green	DP8410NS
Polyolefin - low surface energy	LSE Acrylics	3M™ Scotch-Weld™ Structural Plastic Adhesive DP8010 Blue	DP8010
Sealing & Bonding - Large part lamination	Adhesive & Sealant	3M™ Adhesive Sealant 760 UV White	760

Figure 11. A sample portfolio of products covering the range of Composite bonding application needs

Testing and Prototyping in your Designs

Once a few suitable candidate adhesives are identified based upon their stress/strain behavior general affinity for various types of composites, proper testing of an adhesive for a particular application is of the utmost importance.

An easy, but very useful, test to conduct the adhesion and adhesive strength to certain composite substrates is to test the overlap shear strength. This test is simple to prepare and perform, and is useful for comparing performance across adhesives, substrates or surface preparation methods. The results, however, are specific to particular grades of composite, so it is important to test the actual material in the design. Other tests that are important to conduct are peel and impact tests. These tests are highly dependent upon not only the properties of the adhesives, but also the properties of the substrates and the geometry of the joints. Therefore, published numbers are only relevant when they represent exactly the same test conditions, and again can therefore be used to provide a relatively comparison of performance across adhesives <u>on a particular substrate and geometry.</u>

As shown in Figure 12 below, many adhesives adhere very well to the abraded fiber-reinforced resins (e.g., glass fiber-reinforced polyester or carbon fiber-reinforced epoxy, etc.), reaching structural strength (over 1000 psi). However, some composites are very difficult to bond to and require special adhesives. For example, 3M™ Scotch-Weld™ Structural Plastic Adhesive DP8010 Blue is uniquely formulated to structurally bond to LSE plastics (e.g., polypropylene, polyethylene, polyolefins) – often without the need for any surface pre-treatment. These are two-part, solvent-free, room temperature curing adhesives that come in convenient duo-pack format or, for large applications, in bulk.

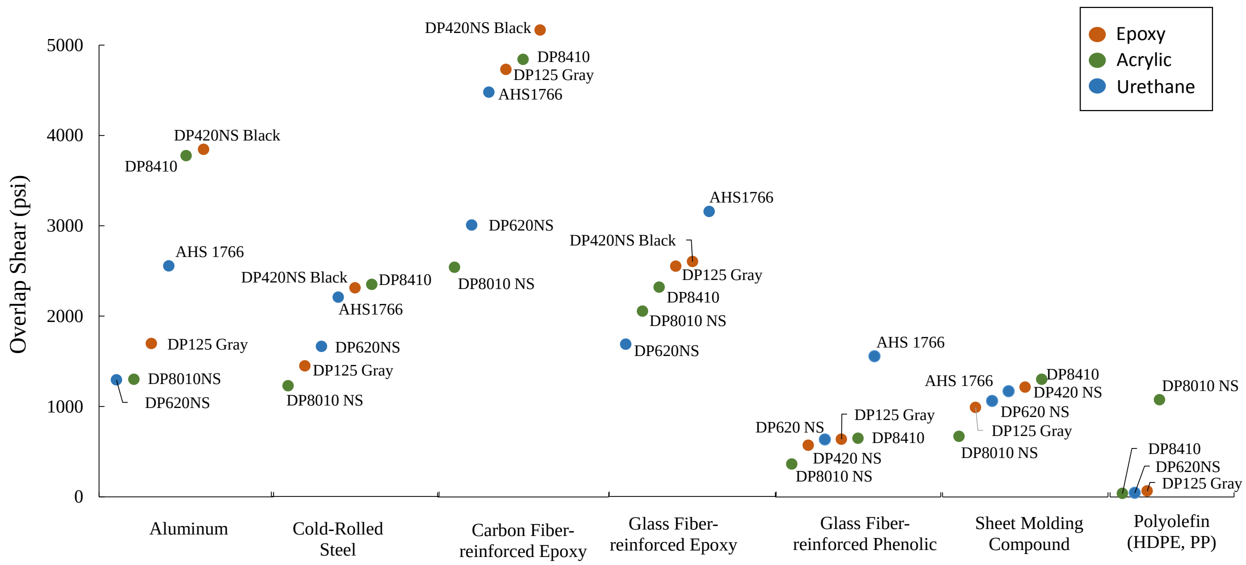


Figure 12: Substrates drive choice of potential adhesive candidates; and also vary in their ability to be bonded. This reflects differences in surface energy and chemistry of the substrates. The chemistry and modulus of the adhesive can also affect the measured joint strength in this type of standardized testing. As described above, adhesion to the substrate is a key criteria; without robust adhesion leading to cohesive failure, one is unable to design to the substrate and adhesive mechanical properties. Because of the wide variety of specific composite compositions, the design engineer should test the specific product to be bonded as well as verifying the necessary surface preparation requirements prior to making a final adhesive selection. It is important to partner with an adhesive supplier such as 3M, who can provide not only material property data but also assist with screening testing to ensure a robust choice is made.

Joint Design with Adhesives

Overall performance is dictated by the joints that are incorporated within the overall design. As noted above, to effectively design a primary or secondary joint, the engineer needs to know and understand several key material properties of both the parts to be joined and adhesive. These properties include: tensile strength, modulus, elongation at break, overlap shear strength, peel, coefficient of thermal expansion, glass transition temperature, etc. Knowing the thermomechanical properties of the two parts that are being joined together is just as important as the mechanical properties. For example, premature bond failure can occur between a fiber-reinforced composite and metal due to the differences in thermal expansion coefficients that can apply undesirable loads onto the adhesive bond; so accommodation should be made if temperature variations are expected in end use. In general, adhesives will provide the highest strengths when loaded in shear, compression or tension; thus it is recommended that any joint be designed to transfer the applied loads in shear and to minimize peel and cleavage forces.

With any joint design that will be joined by an adhesive, it is best to work with a knowledgeable manufacturer of adhesives. It is important that a supplier provides data that is useful and relevant to be able to fully comprehend the benefits of each adhesive chosen for the joint design. This will include information on the thermal and mechanical properties of the adhesives, as well as their general affinity for common substrates. However, testing relevant to specific substrates and geometries will be beneficial before prototyping. At 3M, the technical service offers their extensive experience to help choose the right adhesive for your particular application and substrates of choice. A technical service request can be generated for proper qualification testing to better understand the best adhesive for your application.

Concluding Observations

Composites are increasingly being used in a wide variety of applications to reduce weight, provide improved environmental resistance, improved aesthetics, greater design options and increased stiffness to weight ratio. Adhesives are uniquely suited to joining composites to each other and to different materials, due to their inherent light weight, ability to distribute stress, eliminate potential part damage due to drilling, and capability of joining a nearly infinite number of shapes in aesthetically pleasing ways with minimal post-processing.

To maximize the results of adhesive design, it is important to fully understand the factors that affect how adhesives will perform, so that the correct set of potential adhesives can be quickly identified for subsequent testing and prototyping. Working with an adhesive manufacturer with the ability to provide data and technical assistance will be the most cost-effective way to move towards adhesive bonding of composites.

Technical Information: The technical information, recommendations and other statements contained in this document are based upon tests or experience that 3M believes are reliable, but the accuracy or completeness of such information is not guaranteed.

Product Use: Many factors beyond 3M's control and uniquely within user's knowledge and control can affect the use and performance of a 3M product in a particular application   Given the variety of factors that can affect the use and performance of a 3M product, user is solely responsible for evaluating the 3M product and determining whether it is fit for a particular purpose and suitable for user's method of application.

Warranty, Limited Remedy and Disclaimer: Unless an additional warranty is specifically stated on the applicable 3M product packaging or product literature, 3M warrants that each 3M product meets the applicable 3M product specification at the time 3M ships the product. 3M MAKES NO OTHER WARRANTIES OR CONDITIONS, EXPRESS OR IMPLIED, INCLUDING, BUT NOT LIMITED TO, ANY IMPLIED WARRANTY OR CONDITION OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE OR ANY IMPLIED WARRANTY OR CONDITION ARISING OUT OF A COURSE OF DEALING, CUSTOM OR USAGE OF TRADE. If the 3M product does not conform to this warranty, then the sole and exclusive remedy is, at 3M's option, replacement of the 3M product or refund of the purchase price.

Limitation of Liability: Except where prohibited by law, 3M will not be liable for any loss or damage arising from the 3M product, whether direct, indirect, special, incidental or consequential, regardless of the legal theory asserted, including warranty, contract, negligence or strict liability.

3M

Industrial Adhesives and Tapes Division
3M Center, Building 225-3S-06
St. Paul, MN 55144-1000
800-362-3550 • 877-369-2923 (Fax)
www.3M.com/compositebonding