BONDING OF COMPOSITE PARTS: THE STRUCTURAL ADHESIVES ADVANTAGE

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ABSTRACT

The joining of thermoset and thermoplastic composites is a critical and challenging step in the manufacturing of composite structures. In general, there are many different types of joining methods, which include: mechanical fastening, fusion or sonic welding, and structural adhesive bonding. Although there are advantages and disadvantages with these joining methods, structural adhesive bonding has great potential over other joining techniques. Adhesive bonding allows joining together many different types of materials without compromising strength or aesthetics of the joint. With the trend towards low surface energy thermoplastic-based composites, using structural adhesives can provide many advantages over other commonly used joining methods. The focus of this presentation is to review various structural adhesive chemistries and present recent advances in adhesive bonding to low surface energy composites. A review on processing parameters on bond performance and quality, and selection of the optimal structural adhesive for multi-material bonding, will be addressed.

1. INTRODUCTION

Recent trends and advancements in the manufacturing and cost reduction of composite materials has increased their usage in the transportation, general industrial, and many other markets, in addition to their traditional use in the aerospace field. Driven by increased government regulations on vehicle emissions and end-consumer demand for higher performance products, the need for light weighting and composite materials are progressively 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, and provide greater design options with an increased stiffness to weight ratio [1].

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 when compared to mechanical fastening, how to select the appropriate adhesive to maximize the bonded joint, and testing and prototyping for bonding of composite parts. The following information is meant for anyone with a basic understanding of adhesives and wanting to adhesively bond composites together.

1.1 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 (e.g., 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 (e.g., plastics, metals, and composites) without sacrificing performance properties. Even Low Surface Energy (LSE) plastics (e.g., thermoplastic polyolefin (TPO), polypropylene (PP), and polyethylene (PE)), which in the past had to be mechanically attached or heat welded, can now be bonded with specialty structural adhesives.

To join composites or multiple materials together, mechanical attachments (e.g., clips, screws, etc.) can be used with virtually any surface but do require additional steps to mold or create features for said attachment. This can lead to stress concentrations, which may result in plastic cracking and premature failures of the joint [2]. Also, drilling holes into composite materials will result in a reduction in strength due to the introduction of discontinuities in the matrix and reinforcing fibers. The presence of these holes ensures that the joint strength can never exceed the local laminate strength and can only be half as strong as the designed laminate [2]. All mechanical attachment methods will also 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 joint geometries and substrate combinations that can be addressed.

In addition to forming strong bonds, structural adhesives can lower overall costs and are typically lighter weight than mechanical fasteners. Durability is also improved because structural adhesives can distribute stress across the entire bonded area without introducing any stress concentrations or micro-cracks that will have negative effects on the joint and brittle composite adherends [3]. Another vital 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 and can seal the entire bonding area [4]. 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 engineered composites and plastics. This paper will describe how the adhesive's mechanical and adhesion properties to varying substrates play a key role in the joint design.

2. EXPERIMENTATION

2.1 Materials

There were several different adhesive families investigated in this study. Such families included: flexible epoxy (DP125 Gray), toughened epoxy (DP420NS Black), semi-rigid urethanes (DP620NS and DP335), MMA acrylic (DP8410), low odor acrylic (DP8810), and a specialty acrylic to bond low surface energy thermoplastics (LSE acrylic (DP8010NS Blue)). The substrates used in this study included: aluminum T2024, cold-rolled steel (CRS), glass fiber-reinforced epoxy (FR-4), sheet molding compound (SMC) with class A surface, glass fiber-reinforced phenolic, balanced laminate of carbon fiber-reinforced epoxy, glass fiber-reinforced polypropylene, virgin polypropylene, and virgin high density polyethylene. Substrates were all cut into 50.8 mm wide x 101.6 mm long by 3.175 mm thick and used to test in overlap shear.

2.2 Methods

To test the mechanical properties of the selected adhesives, ASTM D638 Type V coupons was utilized. All specimens were pulled at 50.8 mm per minute and the stress-strain curves were captured. ASTM D1002 has been used to test for 12.5 mm long x 25.4 mm wide overlap shear performance. Bond line thicknesses were controlled with 250 µm glass beads. IPA wipe/abrade/IPA wipe was used to prepare all surfaces before bonding. ASTM D1876 was employed to test for the floating roller peel strength of the selected adhesives. Acid etched aluminum was used as the substrates to collect this data. All adhesive-related data presented here was tested after allowing adhesives to cure for 7 days at room temperature.

3. RESULTS

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 optimal adhesive for a certain joint design and application.

3.1 Understanding Mechanical Properties of Adhesives

Particularly for composite 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 associated with stress-localization. The performance of the joint will also depend upon the modulus of the substrates as well as that of the adhesive used. 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, it is critical to consider some basic mechanical properties of the adhesive first.

In Figure 1, the stress-strain curves are given for a variety of adhesives and tested in accordance with ASTM D638. The mechanical properties of adhesives can be significantly different within an adhesive family and also between the various chemistries, as depicted here. For example, a flexible epoxy (light gray) behaves much differently when compared to a toughened epoxy (dark gray). The stress-strain curve is vital to understanding the physical properties of the adhesive and how it responds to an applied load. When a load is applied, the adhesive will generally first respond elastically and the stress will increase linearly (region where the modulus is calculated). The adhesive's modulus will play an important role in bond performance in the next section. At a certain point, the polymeric backbone of the adhesive 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 fails (e.g., the semi-rigid urethane (light blue)). 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 fail. These stress-strain curves play a crucial role in picking the optimal adhesive for a certain joint design, but they are only a part of the equation.

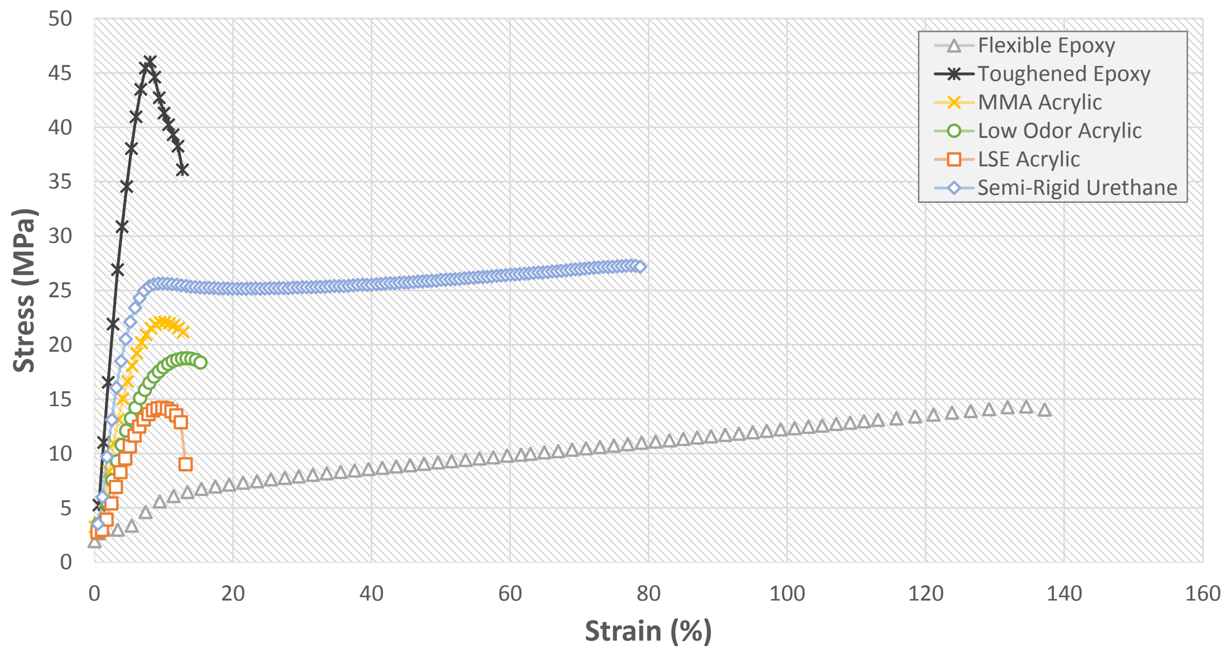


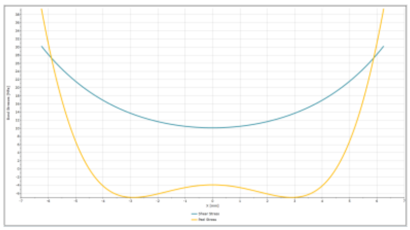
Figure 1. Stress-strain curves plotted for a variety of adhesive families. These plots were generated by applying a load to a dumbbell-shaped specimen in accordance with ASTM D638 and are representative of each material.

3.2 Adhesive Performance with Various Composite Substrates

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. 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 [4]. A general rule would be to balance the capability of wetting a substrate's surface to generate sufficient adhesion (tested by overlap 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.

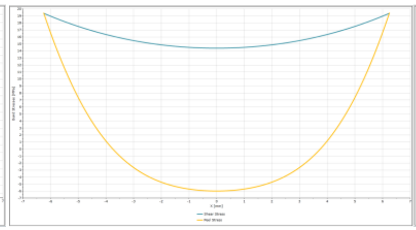
Figure 2 shows calculated shear (blue) and peel (yellow) curves over the length of a single lap shear specimen on aluminum (upper images) and fiber-reinforced composite (lower images). Aluminum has a modulus of approximately 70 MPa and the composite (SMC) has a modulus of approximately 10 MPa. The applied load for this simulation was 200 N/mm bond length. The adhesive and substrate thicknesses were 0.30 and 2 mm, respectively. It is easily approximated with closed form calculations that, for aluminum (Figure 2a), a very stiff adhesive (toughened epoxy with a modulus of 2,000 MPa) is a good choice; whereas the same adhesive leads to almost double the peel forces (yellow line) on the composite material (Figure 2d). This could be fatal for the joint as the upper matrix layer of the composite is likely to fail and lead to premature failure by delamination. An adhesive with a modulus of about 400 MPa gives a comparable scenario on the composite joint (Figure 2e). 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 bond line. 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.

a.)



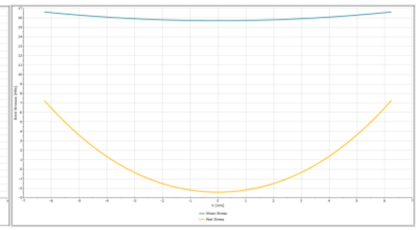
Adherend (modulus): Aluminum (70 MPa)
Adhesive modulus: 2,000 MPa

b.)



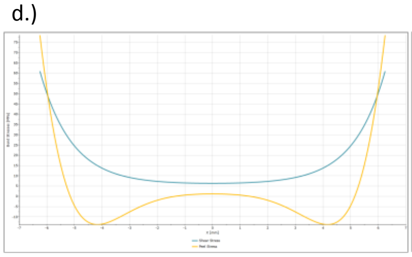
Substrate (modulus): Aluminum (70 MPa)
Adhesive modulus: 400 MPa

c.)



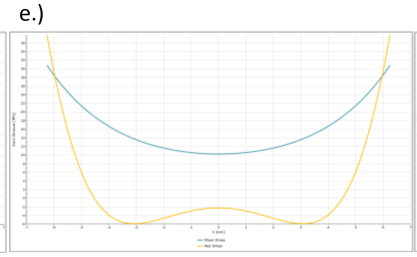
Substrate (modulus): Aluminum (70 MPa)
Adhesive modulus: 70 MPa

d.)



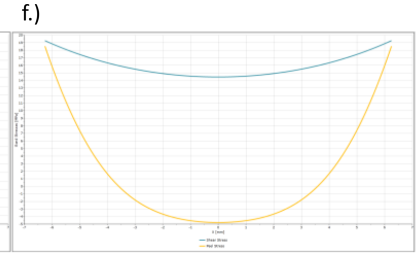
Adherend (modulus): SMC (10 MPa)
Adhesive modulus: 2,000 MPa

e.)



Substrate (modulus): SMC (10 MPa)
Adhesive modulus: 400 MPa

f.)



Substrate (modulus): SMC (10 MPa)
Adhesive modulus: 70 MPa

Figure 2: Closed-form calculations of shear (blue lines) and peel (yellow lines) forces within an adhesive joint as a function of modulus of the substrates and adhesive. Figure 2a-c use an adhesive, with varying moduli listed below the graphs, bonded to aluminum. Figure 2d-f use an adhesive, with varying moduli listed below the graphs, bonded to SMC.

To put the closed-form calculations into practice, Figure 3 shows overlap shear performance of different chemistries of structural adhesives on many composite industry-focused substrates. 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 1,000 psi). The toughened epoxy (dark gray circles) performed very well on many of the substrates, particularly the high moduli substrates (e.g., aluminum and CFRP), by reaching over 4,500 psi. However, as the substrate moduli decreased (e.g., glass fiber-reinforced epoxy, glass fiber-reinforced phenolic, or SMC), adhesives with lower moduli (e.g., flexible epoxy, semi-rigid urethane, or the three acrylic adhesives) showed higher overlap shear strengths. This data reflects well with the closed-form calculations given above. Matching the modulus of the adherend with the modulus of the adhesive is a key driver in creating a joint that will have the highest efficiency of transferring the applied load.

Nevertheless, some composites are very difficult to bond to and require special adhesives. Polyolefins (e.g., polypropylene or polyethylene, etc.) are notoriously difficult to bond, leading many to use bonding techniques like mechanical fasteners or sonic welding. Presented here is a structural adhesive solution to bonding polyolefin-based substrates. The LSE (low surface energy) acrylic reaches structural strength on these types of materials. This adhesive is specially formulated to favorably interact with polyolefins without any special surface pre-treatment and has an open time, or work life, of approximately 10 minutes. As the composites industry moves more towards thermoplastics, specialty adhesives like LSE bonders will become vital.

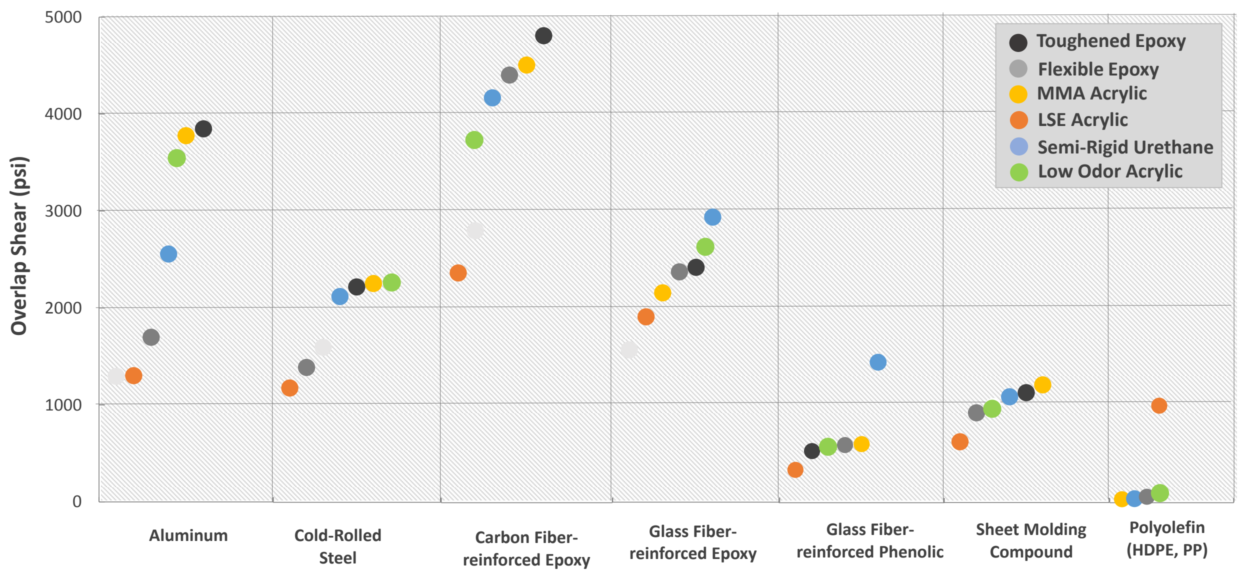


Figure 3. Overlap shear strength of six different structural adhesives on a variety of substrates. These numbers are only relevant when they represent exactly the same test conditions, and again can therefore be used to provide a relatively comparison of performance across adhesives on a particular substrate and geometry.

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.

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.

4. CONCLUSIONS

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.

5. REFERENCES

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