# ADHESIVELY BONDED STRUCTURAL COMPOSITES FOR ASTON MARTIN VEHICLES

*John Hill*
*Ford Motor Company*
*Research and Advanced Engineering*
*PO Box 2053, MD 3135, Dearborn, MI 48104-2053, USA*
Email: dhill12@ford.com

## Abstract

The 2002 Aston Martin V12 Vanquish is one of the most technically advanced cars on the road. From its extruded aluminum space-frame to its carbon fiber transmission tunnel and energy absorbing crash structures, the entire vehicle is adhesively bonded together. Several adhesives are used throughout the structure to optimize performance and processing. A toughened single-component epoxy adhesive is used to bond the aluminum extrusions, whereas a low modulus two-component polyurethane adhesive is use to attach the glass fiber composite body panels. The structural composite parts, such as the front crash structure and tunnel, are bonded using a medium level modulus two-component polyurethane adhesive. This paper will outline the role of adhesives within the Aston Martin V12 Vanquish, in particular the bonding of the twenty plus composite parts. Details of the adhesive selection, corrosion durability and manufacturing issues will be presented for the front crash structure assembly.

## Introduction

From a design, materials and manufacturing perspective, numerous novel concepts were employed for the Vanquish in order to realize performance targets at very low volume output (approx. 1000 vehicles pa). The primary reason for developing such a hybrid design was to obtain a lightweight yet stiff structure at a low investment cost. As can be seen in Figure 1, the main load bearing central structure is fabricated from 35 different aluminum extrusions that are bonded to 34 aluminum sheet parts using a toughened single component (1K) epoxy adhesive. To fixture the geometry during assembly approximately 200 mechanical fasteners are used. Once the heat-activated adhesive has been cured in a 190°C oven, the mechanical fasteners contribute very little to the performance and integrity of the structure. In order to provide long-term corrosion performance of these bonded joints, all of the aluminum parts are sulphuric acid anodized (SAA) to form a protective film. All of the outer surface panels are made from super plastically formed (SPF) aluminum which are bonded to the chassis using a two-component (2K), room temperature cure, low modulus polyurethane adhesive. These exterior panels are held to external surface datum while the adhesive is used to bridge the gap between the chassis and exterior panels. However, some of the most challenging parts on the vehicle are those made of composite and how they are attached to the rest of the vehicle.

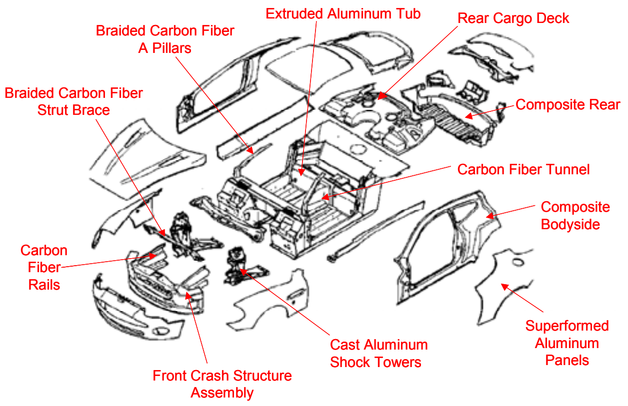

**Figure 1**. Exploded view of the Aston Martin Vanquish

In total there are 25 polymer composite components on the Vanquish (excluding interior and exterior trim parts). The entire front-end crash assembly is made by resin transfer molding (RTM) a complex carbon fiber and glass reinforced preform with an epoxy resin matrix. The crash rails make use of a layered reinforcement that helps provide progressive crush and controlled energy management during a frontal collision. The A-pillars, which provide rollover protection, are made from braided carbon fiber reinforcement over an expanded polyurethane foam core. Once again an epoxy resin is injected during the RTM process to form the desired component. The exceptional torsional stiffness of the Vanquish is achieved, in part, by the large RTM carbon fiber reinforced transmission tunnel. The impressive handling of the vehicle is aided by the carbon reinforced strut brace that ties the front shock towers together. The entire rear assembly is also made by RTM using glass fiber reinforcement and a polyester resin. And finally, the composite bodysides are also made by RTM using a chopped glass and filled polyester resin. The glass preforms for the bodysides (and rear cargo deck) are made using a novel, zero waste, robotic spray forming process called F3P [1].

Several of these composite components were highly loaded structural members that contributed significantly to the vehicle's performance. In isolation, it is relatively simple to predict and demonstrate acceptable performance of these parts. However, one of the greatest challenges facing any designer of automotive composite parts is how to integrate it into the rest of the vehicle (which is usually not composite) without loosing any of its performance, weight and cost benefits. In this paper, one of the most important structural composite components used on the Vanquish, the front crash assembly, will be discussed in detail with regard to how an adhesive was selected to attach it to the cast aluminum front shock towers whilst fulfilling many engineering requirements.

## Front Crash Structure Assembly

### Joint Design

Unlike any other car, the front-end assembly is attached to the vehicle in final trim after the engine and drive train have already been installed. Such a concept aides assembly as the front end can be installed as a module comprising radiator, hoses, headlamps and brackets. The total assembly weighs 60kg and is cantilevered out in front of the cast aluminum shock towers by the 640mm long side rails. As the composite assembly is attached at the end of the process, the adhesive joint has to accommodate build tolerances to ensure hood and fender fit accuracy. The joint also has to withstand crash loads from both frontal and offset orientations. Figure 2 shows a close-up of the final joint. The large bond area ensures that stresses are minimized. The orientation of the groove means that under crash loading the joint is mainly in compression. The tapered groove meant that the front crash assembly could be loaded and bonded in vehicle position, thereby accommodating variability in build tolerance.

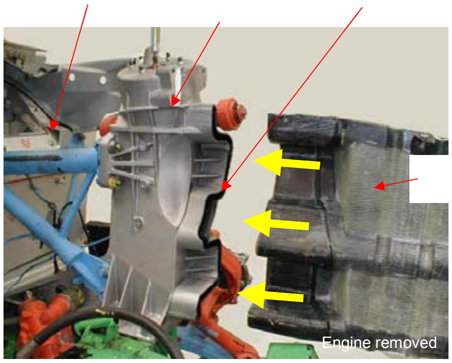

**Figure 2**. Adhesive joint between front crash structure and shock tower casting

### Pretreatment

To ensure long-term corrosion performance of the adhesive bond, the groove in the sand-cast aluminum shock towers was grit blasted and primed with an oven cured epoxy-based primer. The composite crash rails were locally abraded over the region to be bonded in order to remove any external mold release residue.

### Processing

As the front-end crash structure was bonded onto the vehicle in final assembly, it meant that the dispense time and adhesive cure rate were of critical importance. The time necessary to manually dispense the adhesive by an operator and clean up the joint was approximately 10 minutes. Leaving only 30 minutes for the adhesive to cure sufficiently for the vehicle to be removed from its framing jig. It should be noted that the temperature within the assembly plant varies seasonably between 12°C and 35°C. The solution that provided the greatest robustness was to choose an adhesive with a long enough open time to process on the warmest day (35°C), then to use a hot air impingement heating system to locally heat the aluminum casting to accelerate the adhesive cure rate within the joint.

### Adhesive Selection

The adhesive chosen to bond in the front crash structure assembly was determined after considerable laboratory testing, confirmed by full vehicle field-testing. After initial screening trials, the following three, 2K room-temperature cure adhesives were tested:

- Adhesive A - 1:1 mix ratio, polyurethane (PU) adhesive ($E^* \approx 800$MPa at 21°C)
- Adhesive B - 10:1 mix ratio, methylmethacrylate (MMA) adhesive ($E^* \approx 800$MPa at 21°C)
- Adhesive C - 1:1 mix ratio, polyurethane (PU) adhesive ($E^* \approx 600$MPa at 21°C)

## Experimental Setup

### Overlap shear strength

Coupons (100mm by 25.4mm) of the crash rail and aluminum casting were bonded together with each adhesive with a 2mm bond gap. The coupons were made and tested in accordance with SAE J1523 [2] with a 25.4mm by 12.7mm bond overlap. The coupons were prepared with the relevant pretreatments prior to fabrication. The bonded test samples were shimmed within the jaws to align the bond along the neutral axis of the 1125 Instron Universal Testing Machine. The peak failure load and failure loci were recorded.

### Stressed Corrosion Durability Testing

Short (56mm) bonded test coupons with a 25.4mm by 12.7mm over lap area were produced with a 2mm bond gap. Six bonded samples were bolted together in series and subjected to a constant tensile load according to Ford Laboratory Test Method BV101-07 [3]. The pre-stressed samples were then exposed to Ford's Arizona's Proving Ground Equivalent (APGE) corrosion test cycle: 15 minute immersion in 5% (by weight) salt water, followed by a drip dry for 1 hour 45 minutes at room temperature. For the remaining 22 hours of the 24-hour cycle, the coupons were held at 50°C and 95% relative humidity. The number of APGE cycles to failure was recorded for each coupon.

## Creep Testing

Bonded test coupons with a 25.4mm by 12.7mm bond area and a 2mm bond gap were tested in accordance with ASTM D1780 [4]. The bonded coupons were exposed to a constant temperature of 90°C. Displacement was measured using an extensometer.

## Dynamic Mechanical Thermal Analysis (DMTA)

A Rheometrics DMTA 3E was used over a –50°C to 200°C range to determine the tensile adhesive modulus. The 10mm wide by 2mm thick samples were tested in a single cantilever orientation at 1Hz, 2°C/min ramp rate and a 0.1% strain. The glass transition temperature ($T_g$) is defined as the peak value of tan delta.

## Determination of Shear Modulus (Isothermal and Dynamic Temperature Profile)

To determine the build in shear modulus of the different adhesives under both isothermal and dynamic temperature profiles, a TA Instruments AR1000 rheometer was used in an oscillation mode. 20mm diameter parallel plates were used with a 0.75mm bond gap. The strain was set to 0.5% and the frequency was 1Hz. The temperature was controlled via a programmable external induction heating coil. For the dynamic runs, the desired temperature history was programmed into the unit to thermally age the adhesive sample whilst simultaneously taking shear modulus measurements. In all of the data only the magnitude of the complex shear modulus $\left|G^*\right|$ is quoted rather than just the real part (G').

$$\left|G^*\right| = \sqrt{(G')^2 + (G'')^2} \qquad (1)$$

For a cross-linking visco-elastic material at the beginning of the reaction, the complex shear modulus is highly weighted by the imaginary term (G"). It is only towards the end of the reaction when the viscous (or imaginary term) becomes negligible and can be ignored. When determining the dejig time of a bonded part from a fixture, it is important to consider the imaginary term in conjunction with the real term, hence $\left|G^*\right|$ is favored.

# Results

The lap shear strength of the three different adhesives at different test temperatures is shown in Figure 3. As would be expected, the strength decreases with increased temperature. The predominant failure mode for all of the samples was delamination of the composite substrate. Other than confirming that an adhesive bonds to a substrate, simple lap shear specimens reveal little about the suitability of an adhesive to a given application. If a generalization was to be made, then the MMA adhesive appeared to offer a lower performance than the two PU adhesives. One of the weaknesses of any bonded joint is its long-term durability in a corrosive environment.

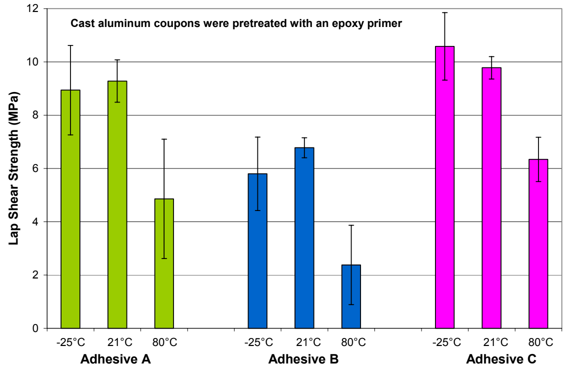

**Figure 3.** Front Crash Structure initial lap shear strength results

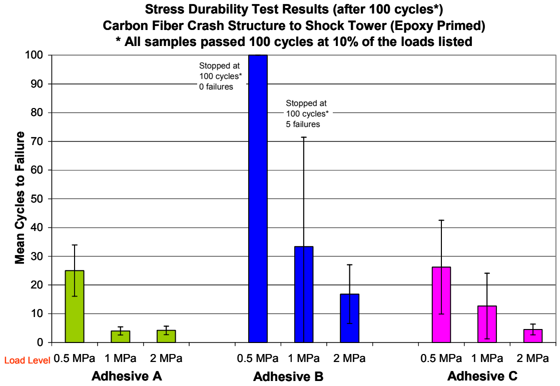

**Figure 4**. Front Crash Structure stress durability results

Figure 4 shows the results of the Ford stress durability test described in the previous section. The coupons were initially loaded to produce a stress of 0.05, 0.1 and 0.2MPa within the bond, which bracketed the peak predicted stress from the full vehicle FE analysis of 0.11MPa. After 100 APGE cycles, none of the joints had failed. After 100 cycles the loads were increased by a factor of 10 in order to try and discriminate between the adhesives. As can be seen from Figure 4, there was a considerable difference in performance, particularly at the lower load levels. The test was stopped after 200 cycles with none of the 0.5MPa loaded MMA samples having failed. In contrast the PU adhesives failed after 26 cycles once the load had been increased from 0.05 to 0.5MPa. The main conclusion from these trials is that the MMA adhesive appeared to have much better long-term corrosion durability than the two PU adhesives tested.

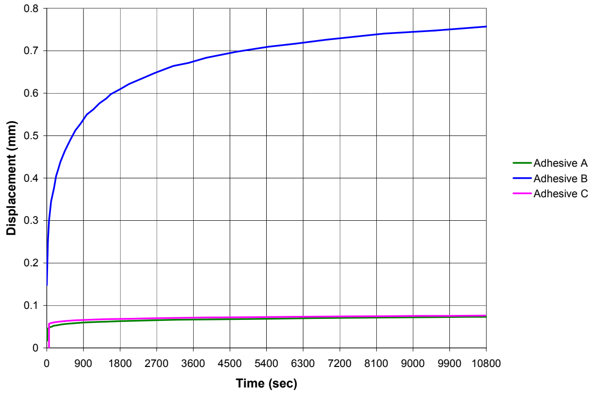

**Figure 5.** Displacement versus time plot for Adhesives A, B & C

Figure 5 shows the creep performance of the bonded joints at 90°C over a 3 hour period. It can be seen that the two PU adhesives exhibited very little creep, whereas the MMA adhesive elongated considerably. It should be noted that the coupons were tested at a stress level of 0.14MPa which included a 20% safety factor over the predicted peak stress (full vehicle FE model).

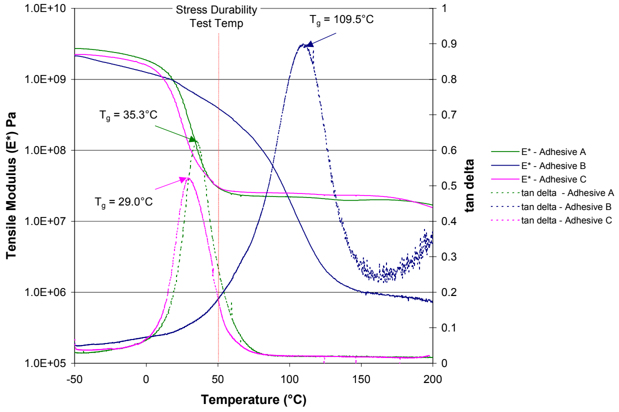

**Figure 6.** DMTA plot for Adhesives A, B & C

Figure 6 shows the DMTA trace of the three adhesives under evaluation. Using the conventional definition of glass transition temperature $T_g$ (peak tan delta) then the MMA adhesive demonstrated a much higher $T_g$ than the PU variants. Up to 100°C, the tensile modulus of the MMA was greater than for the PU's. However, beyond 100°C, the modulus of the MMA diminished considerably. Although the $T_g$ of the PU adhesives was relatively low, they did exhibit the classical glassy and rubbery plateaus. The data shown in Figure 6 demonstrates the importance of temperature effects on the modulus of an adhesive and the decision to be made between a material's robustness to temperature variation and peak modulus at a given temperature.

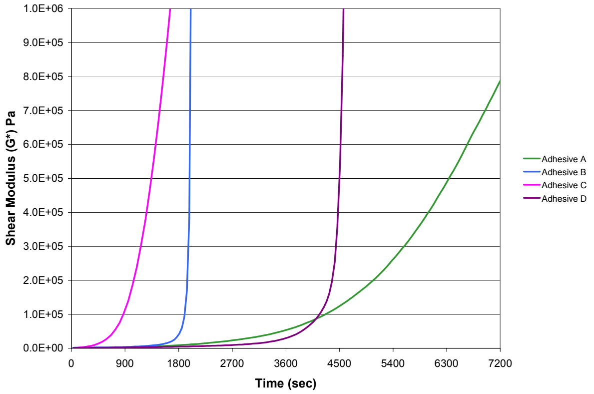

**Figure 7.** Isothermal cure rate comparison of Adhesive A, B, C and D at 25°C

Figure 7 shows the build in shear modulus of the three adhesives at 25°C. The shape of the curves are typical of the different chemistries and reaction mechanisms. The free radical MMA adhesive exhibits a very dramatic step change in shear modulus, whereas the PU adhesives exhibited a more gentle increase in shear modulus with time. It can be seen that the two PU adhesives exhibited very different cure rates. The fourth curve shown in Figure 7 (Adhesive D) represents an alternative MMA adhesive from the same manufacturer as Adhesive B but with a longer open time. It should be noted that cure rate is a function of ambient temperature. Repeating the same experiment at different isothermal temperatures would generate a series of cure curves for each adhesive. In general the shape of the cure will remain constant for each adhesive type, the main difference would be a time shift. In order to make the assembly process more robust an adhesive with a sufficiently long open time was required for use on a hot day (35°C), then once assembled the adhesive was forced cured using a hot air impingement heating system.

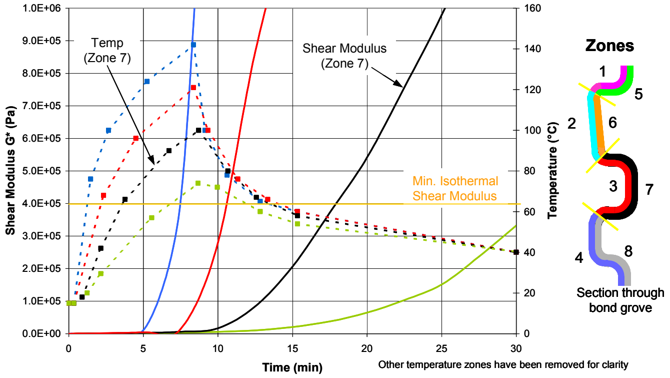

**Figure 8.** Thermal history and shear modulus build rate

Access to heat the bond line was limited to the outer groove edge only. Such a condition meant that the temperature of the adhesive and cure rate varied considerably with time and position. Figure 8 shows the range of temperature histories that were measured within the adhesive bond-line during hot air impingement heating. Also shown in Figure 8 are the shear modulus curves for each thermal history profile.

## Discussion

The results presented in Figures 3 to 7 demonstrate that a holistic approach needs to be taken in selecting an adhesive for a specific application. Performing simple lap shear experiments reveal very little about the suitability of an adhesive to a particular application. There are few applications where shear strength is the limiting factor in a design problem. This is based on the fact that by making geometry changes, it is usually possible to increase the bond area and lower stress concentrations. The accelerated corrosion performance of an adhesive is probably a more important measurable as it indicates how well an adhesive would survive in field exposure. The typical corrosion failure mechanism was interfacial adhesion between the PU and composite substrate and interfacial between the adhesive and epoxy primer. The MMA adhesive exhibited excellent corrosion performance. However, the Ford APGE test is performed at 50°C, whereas the application would likely see temperatures as high as 90°C. The creep testing (without corrosion exposure) highlighted one of the weaknesses of the MMA at elevated temperature. It is speculated that if the accelerated corrosion testing had been performed at 90°C rather than 50°C, the results would have been very different. Measuring the tensile modulus of the adhesive via a DMTA provides a quick way of assessing the physical properties and its suitability for higher temperature applications.

The dispensing and cure of an adhesive are also important considerations. Many people believe that in selecting a 2K adhesive that cures at room temperature, there is little need for extra equipment to cure the product. Although such a statement is true, the chemical reaction rate relies entirely on ambient conditions, which are not typically controlled within automotive plants. There is also the constant trade off between open time and cure time. The use of hot air impingement heating to accelerate the cure of an adhesive provides for a robust solution to both issues of open time and cure rate. In order to determine the minimal cycle time, the shear modulus was determined for 8 regions within the bond line as a function of heating time. An FE model of the front-end assembly was developed and run over multiple time steps using different localized moduli values to see what the maximum predicted sag would be. As expected, the sag, or front-end deflection, was a function of heating time. The deflection was highly non-linear as a function of shear modulus (heating time). At very short times (5 mins) the predicted latch point deflection was 4.25mm, after 10 minutes the deflection was 0.5mm. In practice the Vanquish cycle time was 15 minutes which resulted in a maximum predicted deflection of 0.3mm. The maximum acceptable deflection that could be accommodated by hood and fender adjustment was 0.5mm.

## Conclusions

An overview of the Aston Martin V12 Vanquish was presented showing the extensive use of both structural and semi-structural composites components. One of the critical considerations in using composites from both a cost and performance perspective is how they are attached to the rest of the structure. Adhesives are typically chosen to perform this function as composite materials often suffer from fatigue related problems when holes and mechanical fasteners are employed. There is no one adhesive that is the right choice for every composite bonding application, due to the fact that they are bonded to different substrates. One complex composite assembly was used as an example of how an adhesive was selected for this application. Apart from determining the bulk material properties and bond strength, its corrosion durability was also tested. Finally, the build in shear rate of the adhesive was characterized and used in conjunction with a FE model to predict the minimum manufacturing cycle time.

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## References

1. Chavka, N.G., Dahl, J.S & Kleven, E.D. "F3P Fiber Preforming for the Aston Martin Vanquish", 2001 SAMPE Europe International Conference Proceedings, Paris, France, March 2001.
2. SAE J1523, "Metal to Metal Overlap Shear Strength Test for Automotive Type Adhesives", 1993.
3. Ford Laboratory Test Method BV101-07, “Stress Durability Testing of Adhesive Joints”.
4. ASTM D1780-99 "Standard Practice for Conducting Creep Tests of Metal-to-Metal Adhesives".