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December 2022

White Paper: The Use of Adhesive Injection in Combination with Nodal Structural Joints Typically Found in Electric Vehicles

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Examining an emerging method in automotive bonding and joining

Automobiles currently produce about 15% of the EU's total CO2 emissions, according to European Commission figures. Under new rules, vehicle manufacturers must achieve a 55% reduction by 2030 and carbon neutrality by 2050 [1]. A related demand from car drivers is for longer range for electric and hybrid vehicles – without losing out on performance. Making cars lighter and stiffer - partly to offset the heavy weight burden of EV battery packs - helps to meet these needs. More recently, lightweight materials, such as metal alloys, engineering polymers, structural ceramics and composites have been developed to combat global emissions targets and reduce energy consumption [2]. Traditional pressed steel is being replaced by lightweight alternatives, including aluminium, high-strength steel, carbon fibre, magnesium, plastics and composites. Importantly, a car is no longer made from just one material but from a carefully selected combination that delivers specific advantages depending on the area of application. Adhesive bonding is generally the easiest and usually the preferred method to join dissimilar metals, as well as dissimilar polymers and/or composites. Renault S.A.S. reports that adhesive bonding is a widespread solution for any heterogeneous material combination (Chastel and Passemard, 2014) [3].

As lightweighting, electrification and other megatrends continue to drive automotive vehicle design, we're seeing a demand for new ways to manufacture structural assemblies such as vehicle chassis. The introduction of new materials such as composites and dissimilar metals creates new challenges – especially in bonding and joining. Also, since many dissimilar materials cannot be welded together, new joint designs such as nodal stress joints are becoming more common. This is especially relevant in EV/hybrid vehicles with extra weight below the floor pan. Stress analysis conducted by customers indicates even greater stiffness is needed in the upper structure to avoid the torsional pendulum effects.

Injecting structural nodal joints with structural adhesives can greatly reduce stress concentrations and increase stiffness, which is a key requirement of electric vehicle body structures. Injection joints can also open additional possibilities in design freedom.   Joint stiffness is variable depending on adhesive volume, and the use of adhesive in the joint allows for the use of thinner sections, potentially fewer mechanical fixtures and/or increased structural stiffness. Structural adhesives enable change.

Injection joints in load-bearing nodal stress joints

Benefits of injection joints vs. mechanical fixturing in load-bearing nodal stress joints

- Use of nodal type structural joints has increased in electric vehicles
- Increase stiffness and strength
  - Adhesives contribute globally to stiffness in a structural joint compared to the "point" loading of rivets or bolts
- The use of an adhesive in a nodal structural nodal joint can enable the use of fewer mechanical fixings
- Reduce stress concentrations (point loads)
- Potentially vary the stiffness and strength by the volume of adhesive used
- Injection is a "hidden" process, with minimal cleaning of excess adhesive
- Thinner gauge metal could be used
- Mixed metal joints could be used as the adhesive assists in galvanic isolation

The Project

Structural adhesives in automotive applications are traditionally applied by placing a bead of adhesive onto the surface of a substrate in an open joint or "picture frame" configuration, then bringing the other half of the assembly into contact with the adhesive. This project describes an alternative for applying the adhesive – by injecting it into pre-assembled joints and assemblies.

3M conducted a design study using its 3M™ Structural Adhesive SA9844, which is formulated as an injectable adhesive for automotive joint assembly. The nodal joint consisted of an extrusion and a cast component, which in many applications would be joined with traditional bolts. Both components were 3D printed for proof of concept.

The successful joining of both components using structural adhesive must display measurably consistent coverage, allow for simple variation and control, and reduce point loads where failures can occur. This type of injection joint could be used to support the increasing number of new vehicle platforms which use nodal type stress joints.

Design principle

For proof of concept, 3M created 3D printed models of a typical nodal stress joint, simulating an extruded inner section and a cast outer section component, with the likely bolt holes removed from both. The cast component featured a 2.5 mm adhesive gap with a 1° draft (to 1.46mm), and the radius was matched with the extrusion to maintain the gap at the corners. The cast component also included a 5mm adhesive inlet, and a 3mm adhesive outlet / indicator hole.

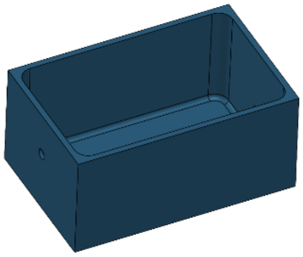


Figure 1: Cast outer component

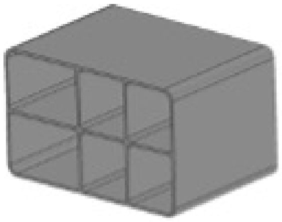


Figure 2: Extruded inner component

Simulation

The goal of the design was to create an enclosed area that still allowed for the smooth, consistent flow of adhesive and allowed for a solid bond across the entire gap. 3M engineers began by performing a simulated test based on the characteristics of 3M Structural Adhesive SA9844. The main metric for measuring the effectiveness of joining the extrusion to the cast material was dynamic apparent viscosity, or demonstration of excellent shear thinning for a non-Newtonian fluid. The density of 3M Structural Adhesive SA9844 was

1150kg/m3. The surface tension of 3M Structural Adhesive SA9844 / air at 25°C was assumed 50mN/m. 3M developed a Computer Aided Design (CAD) simulation using a 5mm diameter adhesive inlet, a 5mm air vent/indicator hole and an adhesive velocity of 50mm per second.

CAD results

The simulation showed a complete adhesive fill of an uncentered gap in just under one minute (59 seconds) even at linear speeds up to 100 mm per second. A 1° drafted bondline gave the adhesive flow a clear direction and shape. An air vent (5 mm) position was predictable and prevented air inclusions.

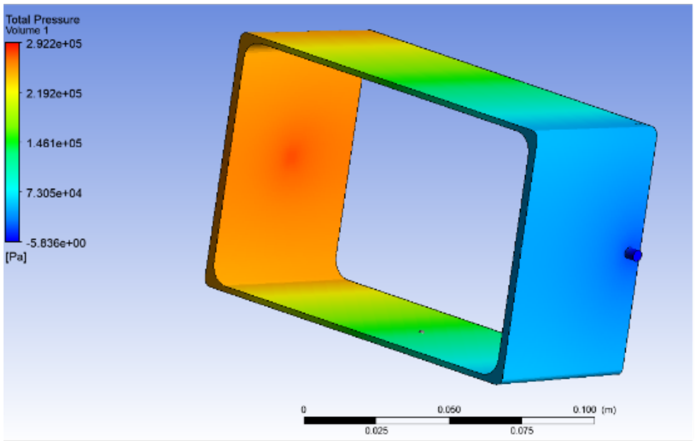


Figure 3: Centered gap

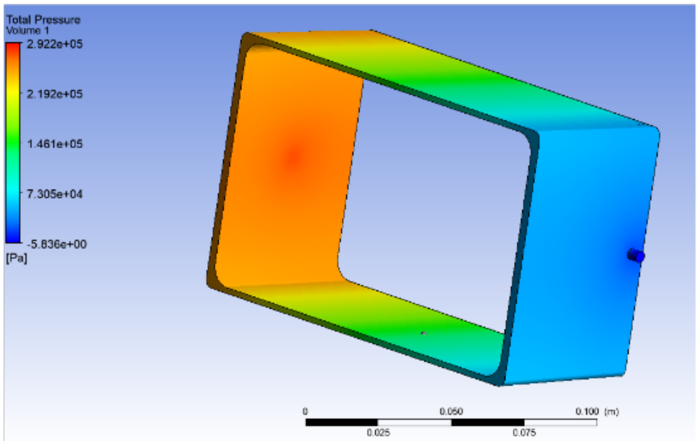
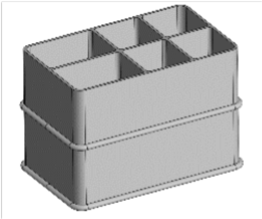


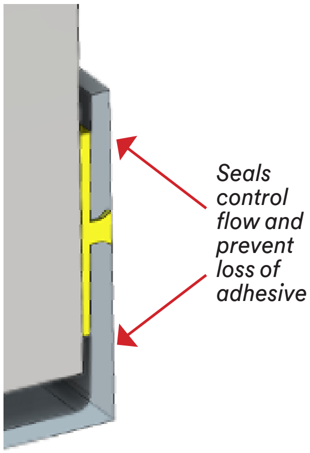
Figure 4: Uncentered gap

Controlling adhesive application: variable sealant beads



To control the adhesive flow and reduce product waste, two sealant beads were robotically applied to the inner component. Two beads of one-part 3M™ Polyurethane Sealant 540 were robotically applied at 4mm and cured in 24 hours.*

The pair of sealant beads were applied to the extruded (male) component, which form an enclosed volume for the adhesive to flow around when inserted into the simulated cast component. Beads were applied to control position and height/profile of the joint to simulate the requirements of standard pumping and dispensing systems commonly used in OEM chassis and EV battery construction.



Benefits of variable sealant bead application as a method of controlling the injected adhesive:

- Sealant beads can be placed anywhere to control area and volume of adhesive
- Sealant is applied to the extruded component only, saving time and material
- Sealant bead is only relevant for controlling adhesive flow and does not affect final joint performance
- Sealant can be applied and cured in advance
- Easy to automate

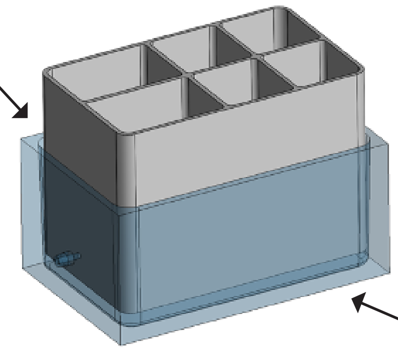
Note: Other 3M sealant versions using 3M™ Polyurethane Adhesive Sealant Accelerator AC61 could reduce cure time to minutes.

Fully automated application

This design also included an automation study which would allow for completely automated injection joint assembly. Following the application of variable sealant beads, the extrusion was robotically inserted into the cast component. Finally, using automated dispensing, 3M Structural Adhesive SA9844 was injected into the prepared joint.

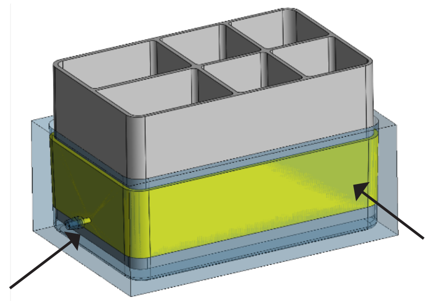
Test Conditions

- **Injection pressure of SA9844 = 6 Bar**
- **Adhesive temperature = 35°C**
- **Fill time = 30 seconds**



Injection of adhesive

With sealant beads in place, the seals maintained the correct designed gap and positions and self-centred upon mating. The controlled rheology of 3M Structural Adhesive SA9844 was ideal for completely filling the adhesive gap all the way around the structure. Though bead performance does not affect final joint performance, the sealant controls the adhesive volume with very little waste at the exit point.



Key Features of 3M Structural Adhesive SA9844

This adhesive features good shear, peel, and impact performance and develops its properties at room temperature, though can be induction cured

3M Structural Adhesive SA9844 bulk properties

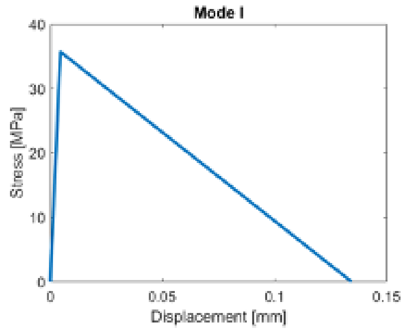
Packaging	400 mL, 50 L and 182 L	
Base	Epoxy	Amine
Density (approx.) g/mL	1,12	1,19
Colour	Black	Silver
Solids in %	100	100
Consistency	Viscous Liquid	Soft Paste
Floating Roller Strength (ASTM D1876)	8.7 N/mm	
Complex viscosity in Pa.s (according DIN EN 17408:2020, A4, 1 Hz, 10 % deformation)	60	100
Mix Ratio by Volume	200	100
Wedge Impact Peel (EN ISO11343)	26 KN/m	
Elastic Modulus (ASTM D638)	2.1 GPa	
Elongation (ASTM D638)	2% - 3%	
Ultimate Tensile Strength (ASTM D638)	35 MPa	

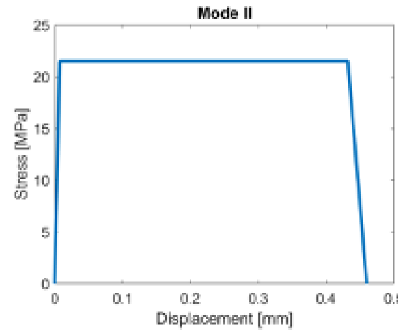
All values for samples cured at room temperature

Verifying durability of 3M Structural Adhesive SA9844 for Automotive Designs

Computer Aided Engineering (CAE) is now an integral part of automotive design and we have created a material data card for 3M SA9844 based on the cohesive zone model (quasi static data shown below).

Parameter	Value
Tensile strength [MPa]	35.74
GIc [N/mm]	2.4
Shear strength [MPa]	21.5
GIIc [N/mm]*	9.5
Young's modulus [MPa]	2365
Poisson's ratio [-]	0.4
Adhesive Thickness [mm]	0.3





The bulk properties shown above can also be converted into LS_Dyna cards, such as Mat_169, to enable customers to conduct internal CAE modelling.

The physical understanding of the fatigue measurements is essential for the durable and reliable use of adhesives in automotive structures [4]. In fatigue, the adhesive test joint is subjected to a known oscillatory stress as a function of time σ(t) (Equation 1.1), and as a consequence, a corresponding deformation or strain ε(t) is produced and measured (Equation 1.2) (BS EN ISO 6721-1, 1996), [9] i.e. where σmax is the maximum stress, εmax is the maximum strain, t the time, ð the phase difference, and ω is the angular frequency of oscillation, which is defined by ω=2.π.f, with f being the frequency.

Equation 1	o(t) = omas. sin (m. t)
Equation 2	s(t) = smas. sin (m. t − ð)

3M has developed internal test capability where lap-shear samples can be placed hot/wet, cold, salt-spray, water immersion etc. while being dynamically loaded between 1MPa and 9MPa. Up to 36 joints simultaneously can be tested.

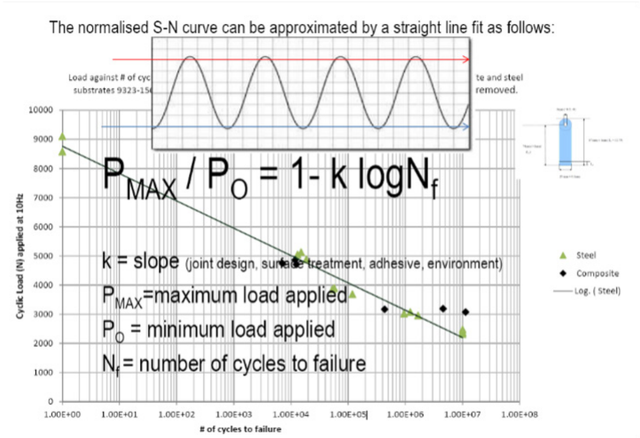


Figure 5: S-N curve line of best fit equation

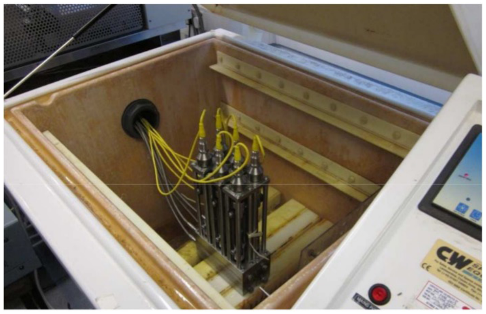


Figure 6: Fatigue Test

3M Fatigue Testing allows specimens to remain in the salt spray chamber whilst being cyclically loaded.

This allows the generation of S-N curves to predict the adhesive test joint's behaviour under specific conditions. This can be a very useful predictor of life cycle performance, such as that shown below. Fatigue testing can also be used to screen the performance of an adhesive with a particular substrate in a nodal joint under specific conditions, such as synergistically testing under a fatigue load while subjecting the test specimens to 50C/98%RH.

Fatigue Testing (ASTM D3166)

Cyclic loading of 1KN (R=0.1) was used on overlap shear test joints that were exposed to 50°C/95%RH during the whole of the test. Fatigue testing in hot/wet conditions is a key discriminator of both adhesive and mechanical performance. All the test joints survived to 10 million cycles (testing stopped) and were then tested to destruction in a stress testing machine. Several OEMs have put a spec limit of 6 million cycles for hot/wet fatigue run under these conditions.

Surface	No of Cycles (testing stopped)	Shear stress MPa (after Fatigue)	Failure mode after lap shear testing
2024T3 aluminium abraded	10,119,023	25	CF
2024T3 aluminium abraded	10,119,066	26	CF
2024T3 aluminium abraded	10,119,139	26	CF

Summary:

This test case study/simulation demonstrates the potential for integrating 3M™ Structural Adhesive SA9844 into a fully automated injection joint processes, allowing the features and benefits described herein to become available to the next generation of electric vehicle designs. Design freedom and performance is now more accessible than ever.

References:

[1] Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. (2019). *The European Green Deal*, COM/2019/640 final (Document 52019DC0640)

[2] U.S. Department of Energy. (2014). *FY 2014 Annual progress report - Lightweight materials R&D*. Vehicle Technologies Office. Available at: http://energy.gov/eere/vehicles/vehicle- technologies-office-annual-progress-reports.

[3] Chastel, Y., and Passemard, L. (2014). Joining technologies for future automobile multi-material modules. *Procedia Engineering*, 81, pp.2104-2110

[4] Wahab, M., Hilmy, I., Ashcroft, I., and Crocombe, A. (2010). Evaluation of fatigue damage in adhesive bonding: part 1: bulk adhesive. *Journal of Adhesion Science and Technology*, 24(2), pp.305-324.

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