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DESIGNING FOR ASSEMBLY STATUS WITH STRUCTURAL ADHESIVES IN THE TRANSPORTATION INDUSTRY

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SUMMARY: A business perspective using the engineering design for assembly concept with structural adhesives in the North American transportation market. The paper will present a historical review of product successes, a modern assessment using adhesion science basics for structural adhesives, and a review of future product development cycles including role of adhesives in the design for assembly needs.

KEYWORDS: Design for Assembly, Structural Adhesives, North American Transportation, Reinforced Composites,

INTRODUCTION

During the late 1960's automotive engineers including design and body product functional departments, began addressing new construction and assembly concepts with the support of aggressive material and equipment suppliers. The use of chemical fasteners like reactive and liquid structural adhesives was being selectively reviewed!

Earlier, structural adhesives had been successfully used in stress-skin configurations involving load-bearing, sealing and extreme environmental-use requirements. Modern prefabricated housing panels as well as engineered wood products were common consumer components. In transportation, advances in the aircraft/aerospace arena like engine-nacelles, wing-rudders, and even specialty blades became common. In other transportation segments like specialty marine and watercraft assemblies as well as mass-transit vehicles, honeycombed panel components preceded automotive introductions.

Vehicle development cycles now required simultaneous team product and process integration. Simultaneous flow was the order of business to address the required time reduction away from the earlier sequential, structured department functions. Communication from design to engineering to manufacturing was evolving , and a supply base was being selected by the original equipment manufacturers (OEMs) to platform design and development with resident OEM engineers. Also, supplier co-locations at the OEM technical centers was common. New dimensional control plans as well as plant flow facilitations were also being supported by mathematical and computer design models.

Now, the definition of structural adhesives included:

- Chemical, polymeric materials
- Ability to transfer/manage energy strains between adherends, exceeding 7 MPa (1000 psi) normal strengths
- Providing a chemical joining/assembly capability
- Exhibiting an acceptable joint failure-mode

In greater detail, structural adhesives were selected due to their durability and processing impact. Durability parameters included:

- Fluid resistance
- Joint-loads at different environmental conditions
- Stress management i.e. energy loss and dynamic impact
- Service temperature range
- Substrate CLTE differences i.e. thermal cycling
- Peel requirements
- Expected joint-life i.e. fatigue

Processing and assembly parameters included:

- Required adherend surface preparation
- Cartridge or bulk delivery system capability as well as manual/automated robotic dispensing
- Adhesive reaction rate kinetics and its rheology
- Handling-strength assembly requirements

Joint design criteria is translated to the product's assembly and service-life:

- Adhesive strain energy balance i.e. elastic modulus and stiffness as creep and temperature function
- Part design needs with assembly simplicity
- Product testing confidence i.e. production part benchmarking

HISTORICAL

Commercial heavy truck and specialty vehicle exterior body panels were the initial focus for reinforced and structurally bonded thermoset composites. The early general purpose polyester fiber-glass reinforced industry was now challenging itself to meet the new demands of improved surface without gelcoats and good surface quality, lower labor part costs and general weight savings.

Initial bonded successes were with International Truck (International Harvester) and Ford Motor heavy-truck hood-fender assemblies, as well as specialty bus and recreational vehicle hybrid plastic/wood and plastic/metal panels.

As with many new business introductions, OEM perceived product and assembly limitations developed encompassing all of the new supplier support areas:

- Molding and assembly knowledge
- Quality assessment and diagnostic troubleshooting/improvement skills
- Tooling investment costs for low volumes
- Management support and market acceptance
- After-market service/repair infrastructure
- Cost effectiveness

Metal hardware and stiffeners continued to be used with mechanical fasteners for body panel attachment points to frame, pillars, roof and chassis where needed.

Disadvantages using structural adhesives encompassed:

- Adherend preparation
- Adhesive chemistry

- Delivery and assembly equipment

As the bonded vehicle closure construction use increased including different thermoset materials and bonded metal reinforcements, the opportunity for vehicle framing design was validated in:

- Off-highway agricultural, military, bus, train, and new light-truck body components
- New specialty vehicle assemblies for high-performance sports cars, the new personal watercraft, and luxury marine assemblies
- Large volume subcomponents, i.e. lamps, bumpers, sunroofs, custom components i.e. spoilers, running boards, etc.

Two-component polyurethane structural adhesives established themselves initially as the preferred adhesive polymer system for panel, hardware and framing assemblies. Goodyear Tire's Chemical Division had patented and commercially introduced PLIOGRIP systems, later acquired by Ashland Inc.

As background, this early adhesive chemistry consisted of the following: prepolymer resin composed of toluene diisocyanate (TDI) base and a hardening resin, a specialty capped polyol, including a plastic wash-primer use, i.e. methylene chloride/isocyanate base. When metal hardware was treated or painted, metal adhesion was assured. Later, TDI was replaced by the more friendly-to-use polymeric methylene diisocynate (MDI) based materials.

A typical generic urethane adhesive system exhibited these properties:

	Prepolymer	**Resin**
Color	**Tan**	**Green**
Viscosity, cps	**28,000**	**12,000**
Density, gm/cc	**1.25**	**1.1**

Bulk Adhesive System Properties @ 23°C

Tensile Modulus, MPa	**17**
Young's Modulus, MPa	**388**
Poisson's Ratio	**0.4**
Elongation, %	**55**
Hardness, Shore A	**60**

Assembly Criteria @ 23°C

Open-time/Working Life, min.	**5-40**
Fixture Handling Strength, min. @ 23°C	**15-200**
Fixture Handling Strength, min. @125°C	**2-8**
Volume Cost, US$/cc	**0.14**

Initial structural adhesive performance specifications existed only in the vehicle OEM's plan for supplier validation. Adhesive dispensing, in-line process controls, including non-destructive testing was beginning to evolve.

New requirements for structural adhesives now demanded :

- Primerless adhesion i.e. no chemical promoters
- Fast-assembly cycles
- Dissimilar materials construction capability
- New service conditions i.e. 200°C paint/sealant temperature exposures

- Recyclability

PRODUCT SUCCESS STORIES

The 1984 General Motors'(GM) Chevrolet Corvette specialty vehicle at 30K/yr was introduced at a new assembly plant in Bowling Green/KY, expanding SMC composite use and structurally attaching closures to a prime-dipped steel space-frame.

Almost at the same time, another GM composite intensive, larger volume and lower cost vehicle was introduced i.e. Pontiac Fiero at 100K/yr. A different and more expensive frame attachment technique was used, i.e. mill and drill pads. GM continued their plastic closure expansion and framing but with a new more friendly, rivet/bond concept, for a large volume, new minivan platform at 100K/yr i.e. the GM200 A-van. Both vehicles success was limited due to critical supply, quality and market acceptance issues; the Pontiac Fiero vehicle was cancelled and the minivan was reskinned to metal. In the mid 90's another series of GM specialty vehicles were introduced to a specialty consumer already familiar with composite bonded components, the large 100K/yr Camaro/Firebird platform as well as the exciting new '97 Corvette. Structural adhesive use was further expanded in this specialty niche vehicle at 25K/yr using the latest adhesive combinations and designed for assembly with short station times using heat-curing/ambient hardening adhesives.

GM also launched a niche vehicle, the EV1, a composite intensive, structurally framed and bonded assembly. Newly announced composite intensive projects include the '03 Cadillac Evoq Roadster to be assembled at the Bowling Green (Corvette) assembly plant.

At Ford Motor Company, engineers aggressively pursued specialty composite bonded components for new vehicles. Novel thermoplastic bumper fascia reinforcements and lamp assemblies were new application market segments. Also, a new cross-truck, interior beam design evolved for a high volume truck line i.e. Explorer/Ranger vehicles; an SMC assembly with metal hardware was bonded within a 60 second assembly time using three heated bonding fixtures and fabricated 5000 units/day. Other new high volume bonded assemblies included metal and plastic attachments to side and rear glass requirements.

More recently, both Ford Motor and General Motors have designed structural reinforced composite pick-up truck boxes for specialty vehicles. A new application segment has evolved and structural adhesives are working with the engineers to provide greater consumer values.

The aggressive thermoplastic resin supply infrastructure with their equipment and fabrication know-how including tooling from Europe began to affect paradigm shifts. The SMC thermoset resin/molding supply base continues to address current disadvantages: high finishing costs; poor recyclability infrastructure; and technology hurdles like higher weight, slower molding cycles, high waste, emissions, and in-mold color capabilities.

Cost-effective aluminum alloys and new steels like high strength, laminated composites are also advancing their position in the future material and assembly process for vehicle product developments using structural adhesives.

As with the early body panel SMC developments, new materials and their assemblies are being driven by successes, advanced by new subcomponent and modular assembly needs driven by megasuppliers and novel niche enterprises. New material combinations are being designed for assembly with structural adhesives for stiffening and lightening major new components like large vehicle bumpers and body-frame assemblies as well improved material for earlier bonded components using reinforced thermoplastic alloys, lightweight metals and advanced composites with different reinforcements. New bonding chemistries i.e. modified methacrylates and toughened epoxies are being customized for high annual use volumes and significant tooling cost savings.

The complexity of bonded assemblies including framing needed to be facilitated for structural adhesive implementation as the vehicle assembly proceeds through the plant from general assembly, body, paint and trim areas. In all cases, different plant temperature and time exposures for chemical attachments exist. The customized bonding chemistries have met these conditions.

Some pictorial product success examples of structurally bonded assemblies include:

- Ford Motors
  - Aerostar Minivan plastic hood and liftgate, followed by Windstar hood
  - Bronco SUV roof-cap and liftgate
  - Mustang and Continental hood, fenders and rear-deck
  - Explorer Sport-trac Composite box
- DaimlerChrysler
  - Jeep Cherokee/Ramcharger liftgate, and Wrangler roof-top
  - JX hood, door, fenders and rear-deck
  - Dodge Viper; Chrysler Prowler

The commercial vehicle & particularly the heavy truck groups expanded their commitment to introduce large plastic hoods, roof-caps and large subassemblies addressing lower tooling costs, shorter product life cycles, new vehicle modifications, and all the other earlier change drivers with bonded assemblies.

Global consolidation was now beginning to emerge: Daimler-Benz acquired Freightliner; PACCAR acquired Kenworth and Peterbilt; Renault VI and Mack; Volvo AB enhanced its North American position with White and GM Heavy- truck equity. Another more recent acquisition wave further consolidate Ford Heavy Truck to Freightliner, and Volvo Truck now owns Renault/Mack. Fiat's Iveco and GM's/ Isuzu remain independent, at this time. International Truck, formerly Navistar, has reorganized to Engine and Truck Divisions.

Some recent commercial vehicle engineering highlights included:

- Mack Truck, late 80's, developed a new composite cab-over-engine (COE) truck in this timeframe demonstrating that an all-plastic structure and its assembly criteria can be achieved cost-effectively and technically superior
- PACCAR and Freightliner, mid 90's, developed a bonded plastic/aluminum cab modular

Agricultural/Off-highway OEMs developed low-volume sub-component supply base with new thermoset molded skins for improved weight savings and easier paintability, but more difficult to structurally bond. Caterpillar, New Holland/Case and John Deere are the major vehicle manufacturers who also have global assembly needs.

The market dynamics for increased structural adhesive use also germinated serious structural adhesive competition in the chemical industry! Value-added extensions of current surface science expertise (like adhesion promoters, cleaning agents, etc.), coating and finishing expertise (like metal, plastic prime coats and topcoats), and complementary sealing/low-tech bonding volumes developed momentum for new polymer developments. Naturally, companies with resin expertise enjoyed even a greater understanding to future adhesion, processing and performance challenges.

DESIGN FOR ASSEMBLY UNDERSTANDINGS

Structural adhesive targets are now being defined for the future and involve changing industrial trends:

- Fast assembly times, possibly with hybrid joining assists, and no damaging adherend energy activation
- In-line, minimal/no adherend surface preparation
- Ease of disassembly/OE rebondability
- Environmentally acceptable
- Cost-effective

What is driving these changes.

- Greater fuel economies
- Increased modular component use
- Increased environmental attributes, like recylability
- Increased consumer friendliness, like less noise, vibration, stiffness

Material engineering specifications at the vehicle technical centers were changing from the original material specific, i.e. unique supplier to a new global, performance level standard. An inherent risk was given—incomplete lab data had little correlation with part assembly and durability needs. To the structural adhesive supply community, a "gray zone" was emerging even though competitive dynamics would address benefits best.

OEM design and manufacturing engineers needed to search, to define, and to establish meaningful data for their new structural adhesive performance and assembly targets by:

- Benchmarking earlier bonded assembly successes with new adhesive polymer properties
- Developing meaningful and standardized test methods with production substrates using assembly parameters for screening desired new adhesive materials for purchasing and final production validation
- Assisting new computer-aided design (CAD) needs for joint understandings using new stress-strain adhesive polymer properties including new mathematical models and correlation
- Developing adhesive rheological understandings required for meter-mix machine dispensing requirements including central-header feed systems to the required dispensed bead configuration for best flange coverage and minimal readthrough concern due to different material thicknesses and coefficient of linear thermal expansion (CLTEs)

Continued unknowns exist with limited data:

- New composite molded resin and metallic adherend materials require extensive surface understandings for best adhesive practice
- New assembly needs require faster adhesive polymerization to achieve handling strength with long working times
- Nonstandard recyclability
- Undesirable high manufacturing and finishing costs

- Poor technical applications' innovation with respect to eliminating current thermoset finishing issues like surface and edge defects, i.e. "pops," their continued high specific gravity, and slow molding times

New product development cycles are shorter today as the conceptual, engineering and manufacturing phases contain various tasks.

In concept, focus remains on:

- Part geometry
- Performance Requirements
- Potential Materials
- Feasibility Study for Product Performance and Cost
- Possible Manufacturing Methods

In engineering, focus remains on:

- Detailed engineering and Assembly
- Analysis of System for Assembly itself
- Testing
- Redesign

In manufacturing, focus on:

- Tool and Fixture Design
- Selection,Evaluation and Implementation of Equipment
- Preproduction Runs
- Production Part Testing
- Engineering Analysis
- Final Cost Analysis

A structural adhesive supplier, usually from a specialty chemical house, must provide solutions to the following needs:

- Ability to manage/transfer joint stresses between selected adherend materials and accelerated tests balancing elastic modulus as defined by stress, temperature and fatigue conditions
- Ability to overcome known surface interfacial energies at affordable cost in similar accelerated test environments
- Ability to assemble friendly required cycle-times and worker environment
- Ability to be satisfactorily field-serviced
- Ability to be cost-effective

As the product design focuses on adherend materials which must be globally available and similar to one standard, additional material data needs include:

- Property changes/data due to non continuous manufacturing as well as required accelerated failure testing
- Known surface characteristics required for both structural bonding and wet-finishing (painting)
- Lowest weight/strength ratio
- Affordable

Adhesive understandings for surface interfacial understandings include:

- Critical wetting tension less than the adherend's surface energy
- Low viscosity in order for an achievable equilibrium contact angle during clamping time
- Morphology understanding
- Removal of adhesive's weak boundary layer or adhesive compatability
- Chemical/covalent bonding functionality to known surface/primer

It is important to assess what surface preparation and at what cost is essential for the product's life exposure.

The assembly design may utilize a hybrid approach, a mechanical locking and/or secondary fastening system as the structural bond hardens with measured time/temperature.

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The product design must address following with

- Minimum peel stress, using peel stoppers and/or preventing peel edge propagation
- Changing joint construction, widening the end of thinner adherend, or adding insert to the edge or doubling the end of edged joint

Stress analysis indicates that the adhesive stiffness is a major dictate! But, a selected adhesive system should remain elastic and be minimally susceptible to load and temperature changes. In reality, these considerations are essential:

- Balanced adhesive modulus for strain energy density management
- User available application and curing capability
- Appropriate economics for the end-use product design need

In greater detail, the bond surface and joint requirements will include:

- Bond-surface preparations in line with end-use need
- Appropriate considerations for thermal expansions
- Minimization for adhesive peel at bind edges
- Design for adherend failure
- Design adhesive failure over small bond region
- Design for worst case adhesive properties
- Design for elastic adhesive performance in lapshear and not plastic in stress

Now, the assembly process requires:

- Lowest activation temperatures
- Longest open-assembly times with shortest assembly times
- Minimal adhesive waste

As an initial screen structural adhesive qualification, product-testing entails:

- Lapshear and cleavage/peel/energy strain testing with controlled materials and assembly process
- Chemical properties to include standard handling, shelf-life, and descriptive test
- Cost-effective

A second tier test series can include:

- Accelerated environmental and fluid resistance lapshear/etc testing
- Simulated part testing
- Development of failure standards and safety levels

- Delivery capability
- Dis-assembly and repair

New, in-process assembly controls now include:
- Material substrate tests with proper surface understandings/conditions
- Adhesive resin flow and pressure controls parameters
- Assembly time controls i.e. open-time, clamping-fixture times at specific temperature/humidity levels to best manage strength development times
- Inspection tasks
- Product-use time or when it can be used following assembly

Future engineering efforts, like those quoted from the DaimlerChrysler's advanced engineering studies for the Chrysler Composite Vehicle (CCV) mule-builds with large, cost-effective, in-mold colored, structurally bonded reinforced thermoplastic panels will further expand and drive progress to meet the future U.S. '04 needs. The vehicle assembly design efforts are addressing:
- Fast, low/air-cure temperature hardening adhesive curing systems
- Minimal/no bond surface area preparation, including hybrid fastening techniques
- Using newly assembled/bonded modulars from chassis frame, and components like floorpan, and painted panels structurally attached
- Cost-effective

CONCLUSIONS

New structurally bonded component assemblies and plant framing needs are:
- Lower manufacturing costs
- Less assembly space
- Less tooling costs
- Less labor input per vehicle
- New material efficiencies
- Continued material/fastener weight savings
- More stiffness, less noise and harshness
- Continued part consolidation

As always, history will continue to be a good teacher for the future:
- New materials are driving changes addressing needs for lower weight, part consolidation and less cost
- Structural adhesives are evolving and being customized to meet product design and assembly needs for closures, framing and modulars for specialty assembly
- Partnerships with material, tooling and processing suppliers are required to overcome current technical hurdles as research and development, applications development, and intellectual property are driving global alliances
- Testing and modeling capabilities are required to evolve with the above to confirm learnings and shorten product launch cycles
- Be ready to accept more change

Success metrics will definitely include the following:
- Satisfied end-user customers with newest technology use
- Solid and profitable supply and manufacturing base
- Global intellectual property accessibility for future growth

North America's bonding opportunities and future efforts are easily translatable to other regional industrial and economic areas. More communication channels and support teams are available today in the given globalization efforts. Well-guided management efforts and partnerships with an engineering/manufacturing integration team will ensure success. The specialty chemical supply base providing structural adhesives will continue to participate at the design for assembly efforts.

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