Big Glue!

Testing the Scalability of Adhesives in Architecture and Design

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Abstract

This paper documents the questions, methods and outcomes of “Big Glue,” a research collaboration among students and faculty from Cal Poly, San Luis Obispo’s chemistry and architecture departments that explores the potentials of structural adhesives in architecture and design. The project asks how adhesives can be more broadly used as work increases in size from the scale of models to full-scale construction.

Our focus is on aluminum structures. We looked at existing adhesive use in construction and in the automotive industry, where adhesives are increasingly used on aluminum and aluminum composites to reduce weight and consequently increase fuel efficiencies. We see potential overlaps between automotive and architectural applications of adhesives in sheet metal structural skins.

We began at a small scale to get acquainted with adhesives and to test using bonded joints in applications that would typically be welded or mechanically fastened. Our team formulated custom adhesives based on parameters we defined as specific to architecture and construction, then tested this lab formulation and other adhesives on glued joints at three scales—extra small, small and medium—in the form of test coupons, a “ravioli” structure, and furniture.

Working at the scale of furniture allowed us to test material interactions on load bearing seams that are structurally analogous to larger scale architectural applications. Using adhesives instead of welds or mechanical fasteners allowed us to work more fluidly between scale models, digital simulations, and final products. This research lays the groundwork for scaling up to large and extra-large projects.

Keywords: Materials & Construction Techniques, Design/Build

Adhesives Applications

There is precedent in engineering and chemistry for using adhesives in large-scale sheet metal assemblies such as aircraft, car bodies and other structural skins, especially at the original equipment manufacturer (OEM) stage of development. Recent advances in adhesive and bonding technology are being promoted by the increased use of thermoplastic and thermoset composites in aircraft fuselages, automotive components and spacecraft. These composite assemblies are often chemically bonded together before the incorporation of mechanical fasteners as a means of introducing safety redundancy into the product. Car, truck, plane and rail bodies that substitute adhesive bonding for welding and fastening are lighter, stiffer and more durable.

Adhesives have been used in the aerospace industry for interior and airframe applications that require strong composite-to-composite bonds and composite-to-metal bonds with high mechanical strength and chemical resistance. This allows for the structure to require fewer or no fasteners, and consequently a lower adherent thickness. Furthermore, adhesives are used in specialized applications such as shims and surfacing films for lightning protection. Adhesives also have been employed for repairs where the structural integrity of key aircraft components is critical.

Automotive applications of adhesives are similar to the demands of the aerospace industry, requiring high mechanical strength and allowing for the bonding of two dissimilar substrates. With the increased use of composite materials in automotive parts, the need for automotive adhesives has grown. Not only are adhesives practical for joining two dissimilar parts but can lead to lower weight by eliminating the need for mechanical fasteners.

In buildings, adhesives are widely used in concrete, wood and metal construction and in applying finishes (carpet, tile, etc.) In building envelopes, adhesives appear in plywood, cross laminated timber, structural insulated panels (SIPs) and Insulating Concrete Forms (ICFs). Structural silicone sealants are used to secure glass in curtain wall systems and steel façade systems also rely on adhesives.[1] Finally, fiber reinforced composite building components and composite building systems are emerging areas where adhesives are essential.

Composite systems in architecture, like in the automotive industry, can reduce waste in design. Bill Kreysler frames an argument for a more streamlined process of design and construction in his article “Waste and Tolerance in Design and Construction” as follows:

> Building materials developed during the industrial revolution, when energy was cheap and raw materials seemingly abundant, are not suited for our world today. Buildings made with these off-the-shelf products waste energy and natural resources and take enormous amounts of time to assemble....New materials must be found, design methodologies must evolve, and most importantly, these materials and designs must integrate into the workflow from the ‘drawing board’ to project completion.

Beyond their impact on waste, adhesives have potential to streamline project workflow because the representation of glued joints is the same at model and full scale, and their construction is more straightforward. Use of adhesives has clear structural advantages as well. Substituting adhesives for mechanical fasteners eliminates corrosion risk and catastrophic failure. Adhesives eliminate stress concentrators around drill holes and the fastener/body interface. And they create stiffer and more continuous bonds.

Greg Lynn describes the situation in “Chemical Architecture” as follows:

> There is a sea change going on in the world of construction: the shift from assemblage to fusion. In material terms this translates into a shift from mechanical to chemical attachments. More simply, things are built without bolts, screws, nails, or pegs; instead, they are glued.[3]

While our project’s scope is glued sheet goods, not composites per se, we see parallels with composite materials in our shared interest in using adhesives to reduce waste and streamline project workflows. We also see aesthetic advantages to using adhesives, particularly in joint design and its impact on the legibility of building massing.

There are differences in the parameters for glue selection between automotive and architectural adhesives applications. Architectural applications are subject to similar environmental forces as cars, but unlike automotive applications, construction occurs in the field rather than on the assembly line. A primary factor in selecting adhesives for architectural use is their suitability for application in variable (e.g. minimally controlled) conditions. This means selecting a glue that can be applied to minimally prepared metals and that can cure at a range of normal room temperatures, without any special processing (UV, moisture, extreme pressure.). A secondary factor is strength. There is more latitude in architectural applications than in automotive, for example, where impact resistance is a major consideration. For us, this means prioritizing field-application parameters over maximum strength.

Adhesive Formulation and Testing

Based on the parameters of suitability for field-application and reasonable strength, we formulated a custom adhesive and tested its shear and peel strength at a small scale.

We limited our study to epoxy adhesives. Although acrylic adhesives can be more amenable to being applied in field conditions because they require a less pristine surface for a good bond to form, epoxies are generally stronger. Structural bonding using epoxy-based adhesives is a mature technology in aerospace and automotive industries, where adhesives are used to join structural components and skins without fasteners, or in areas where anticipated stress on the material necessitates adhesive as well as mechanical fastening of components.

We used two commercial, over-the-counter adhesives: Gorilla Weld Steel Bond Epoxy and JB Weld KwikWeld Steel Reinforced Epoxy. The Gorilla Weld Steel Bond Epoxy product consists of a methyl methacrylate and methacrylic acid-based resin, crosslinked with a methyl methacrylate based hardener containing talc and fumed silica as inorganic fillers. Presumably, the inorganic fillers are supplying mechanical toughness and enhanced ability to mechanical interlock the adhesive with a substrate material. JB Weld KwikWeld is a bisphenol-A based epoxy resin containing carbon black as an inorganic filler meant to provide mechanical toughness and improved mechanical interlocking with the substrate.

A third material was a lab formulated epoxy adhesive consisting of a stoichiometric amount of EPON 1001-CX-75 and EPIKURE 3115-X-70. EPON 1001-CX-75 is an epoxide resin in a 25% solvent mixture of methyl isobutyl ketone and xylene. EPON resins are typically used in industrial maintenance coatings where chemical resistance, corrosion resistance, and low or no color is desired. EPIKURE 3115-X-70 is a high molecular weight reactive polyamide crosslinker delivered in xylene as a solvent. EPIKURE cross-linking resins are chosen for their water resistance, chemical resistance, and corrosion resistance.

The over-the-counter glues were chosen for their commercial availability and use as a general adhesive for multiple applications which may include smaller scale applications and provide insight and inspiration into the scalability of adhesives. The lab formulation was used in a “neat” fashion, without the addition of additives, in order to assess the baseline performance of the polymer adhesive, and was chosen based on its prevalence in the industrial coatings sector.

All three adhesives systems studied here are prevalent in industry applications and are cost effective. Different fillers and solvents are used in each, and some structural resin features are unknown due to trade secret protections, but the class of materials presented here nonetheless represents a “builders basic toolkit” of polymeric adhesives.

Fig. 1. Big Glue lab-formulated epoxy

For each glue, we tested lap shear strength. The tests were performed following ASTM D1002.[4]

For most of the adhesives, the maximum load of the adhesives increased with more areal coverage of the lap joints, allowing for a weaker adhesive to compensate through a larger covered surface area, increased interfacial adhesion between bonded parts, and more bulk adhesive to contribute to carrying a structural load. However, the JB Weld showed the opposite trend, likely due to the curing mechanism or application of the JB Weld, allowing for a void to form and create a weak point that allowed for fracture of the adhesive resulting in cohesive failure within the bulk body of the adhesive. Maximum load of the Gorilla Weld reached 16000 N (approximately the bite force of a 5 meter long saltwater crocodile), which should be more than sufficient for the architectural applications described.

We also compared lap shear strength to peel strength for one pair of 1/8” thick aluminum samples. The shear strength was much greater than that of the thinner test coupons (13,000 N) and the peel strength was 850 N.

Adhesive		
Lap Joint Overlap (inches)		
Shear Strength (ASTM D1002, N)		
Gorilla Weld		
1	*2*	*3*
1,500	10,000	16,000
JB Weld		
1	*2*	*3*
7,200	7,500	6,000
Lab Formulation		
1	*2*	*3*
1,700	3,250	3,750

Lap Joint Overlap (inches)		
Shear Strength (ASTM D1002, PSI)		
Gorilla Weld		
1	*2*	*3*
112	375	400
JB Weld		
1	*2*	*3*
538	281	150
Lab Formulation		
1	*2*	*3*
127	122	94

Fig. 2. Adhesive Shear Strength Tests, first round results in Newtons and PSI

Considering one of our parameters was reasonable strength (compared to a welded joint, but not needing to withstand crash impact, for example), our lab formulation performed fine. Although it wasn't the strongest glue, the lab formulation had other advantages. Working with bulk material allows for lower costs compared to commercially available adhesives. It also provides a baseline to compare to and adjust the formulation to the desired properties (scalability, mechanical strength, environmental resistance).

Joint Types for Bigger Tests

While the adhesives tests were being conducted, students evaluated joint types and potential forces they would be subject to in the context of furniture. We reviewed many metal furniture precedents to identify joint types that could be reinterpreted with adhesive bonds. Most of the precedents were welded. Two precedents of note are Oskar Zieta's hydro-formed metal Plopp Stool and Joris Laarman's Asimov chair.[5,6, 7] Both of these are made with sheet metal and neither relies on straight folds for its shape, as is typical for most of the other sheet metal furniture we reviewed.

We developed some sample joints for our next scale of adhesives testing according to three areas of interest- a curved lap joint subject to shear and peel forces, a perimeter lap joint subject to peel forces only, and a mixed material joint between wood and steel rod.

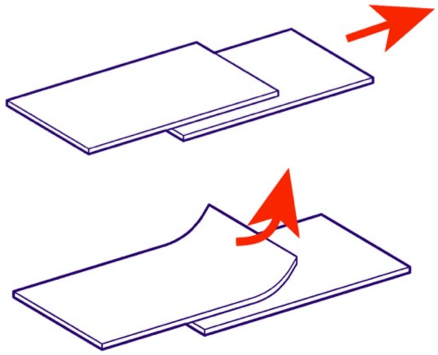

Fig. 3. Shear force (top), peel force (bottom)

Case Studies: Student Projects

Each student developed a piece of furniture to test the field application and strength of adhesive joints with various glues. Each of the three case studies and its successes and failures is described below.

Case Study #1: Ravioli

The Ravioli are made from "inflated" sheet metal. Two sheets are laminated along the perimeter and a hydro-forming process forces the sheets to warp apart. Oskar Zieta / Prozessdesign's FiDu technique is a precedent. FiDu, however, uses welds rather than glue. Within the context of this project, a test of outward pressure on metal sheet seemed like a useful intermediate step between test coupons and full-scale furniture.

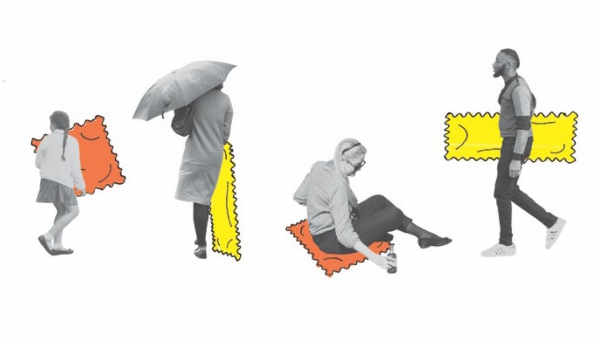

Fig. 4. Ravioli (Diagram author: Bennett Mueller)

Initial Ravioli tests provided feedback about surface preparation. While the test coupons for the first round of shear strength tests were prepared in lab conditions per ASTM D1002, The Ravioli was produced in a considerably less controlled studio environment. The surface was lightly abraded and de-greased, but conditions were more similar to what one might encounter in the field on a construction site. The hydro-forming was done using a conventional pressure washer connected via hose to a nozzle embedded in the perimeter of the Ravioli. Some of the first Raviolis exhibited super localized cohesive failure at points along their perimeters. The Ravioli, when inflating, are only as strong as their weakest point - a leak will cause the hydro-forming process to fail.

Epoxy provided a major obstacle to the tests, resulting in a number of failures. Because Ravioli need glue spread over a large area, epoxy's viscosity and set time were both problematic. Using a polyurethane adhesive that reacts with a few drops of water fixed this issue. The thin polyurethane easily spread across the entire surface of one sheet while water was put on the other sheet. The two were then sandwiched together, the water started the glue curing, and the foaming polyurethane filled any potential gaps.

The force required for plastic deformation of the metal needed to be less than the adhesive strength. To assist with this, clamps were used to push the edges of the Ravioli towards each other as the pressurized water entered and pushed the centers of each sheet apart. Thin (30 ga.) galvanized steel gave the best results. After inflation, the Ravioli was filled with expanding foam and the edges were sealed with epoxy.

Fig. 5. Ravioli during hydro-forming (photo credit: Bennett Mueller)

Future hydro-forming would require better adhesion and glue that had stronger peel strength. It is likely that polyurethane or acrylic adhesive would continue to perform better than epoxy, even with additives to decrease viscosity or lengthen set time.

Case Study #2: Funky Legs

The second student, Mariana Puig, was interested in mixed material glued joints. Her furniture is made from 12 bent steel legs attached to three wooden planks, and has both metal-to-metal connections and metal-to-wood connections.

Fig. 6. Funky Legs (photo credit: Bennett Mueller)

To make the legs, she built a jig with three cut pieces of rebar around which to bend heated steel rod. She welded each steel leg into a closed loop before powder coating them. The decision to weld rather than glue the legs was made based on an intuitive assessment of joint geometry- because the legs are ¼" diameter rod there isn't much surface area for adhesion. We thought a weld would have a better chance for success. Glue was reserved for wood-to-metal connections. The wood elements have 12 grooves cut to receive the legs.

After analyzing the joints and doing some tests, we concluded that although the glue was theoretically strong enough to keep the wood and the metal together, the shape of the joint would support a welded connection better than a glued one. Again, joint geometry was not ideal for an adhesive bond. For any future mixed material connections, better joint design would be needed to support strong adhesive bonds.

Case Study #3: Three Egg Whites, Soft Peaks

The third project was a chair designed as non-concentric truncated cone that overlaps at one seam. This shape provided good testing conditions for our glue, as the joint was subject to both peel and shear stress. The truncated cone would be rolled into shape from a single sheet of 1/8” thick aluminum. This design minimized the appearance of all artifacts of the fabrication process as a way of highlighting the seam. Three Egg Whites, Soft Peaks operates somewhere between chair, chaise lounge, and dog bed exhibiting characteristics of all three.

There were several rounds of iteration at the study scale and subsequently as full-scale prototypes to test the angle of the tilt and sizing of the chair. Initial studies had trouble translating to the full-scale and would tip over on its own weight. The center of gravity would shift depending on the position of the occupant. The wide base was necessary to accommodate for a wide variety of positions. In addition to the use of epoxy, other fabrication constraints included the size of the waterjet CNC mill and the rollable thickness of aluminum in a hand-powered plate rolling machine. The most difficult part of the fabrication process was the rolling of the aluminum sheet metal. At ⅛” thick, we were pushing the limits of the hand-powered plate rolling machine we had available. In addition, we had to manually adjust for a continuous change in radius along the entire truncated cone. The glued joint, therefore, needed to withstand stresses internal to the aluminum and its tendency to spring back to a flat shape.

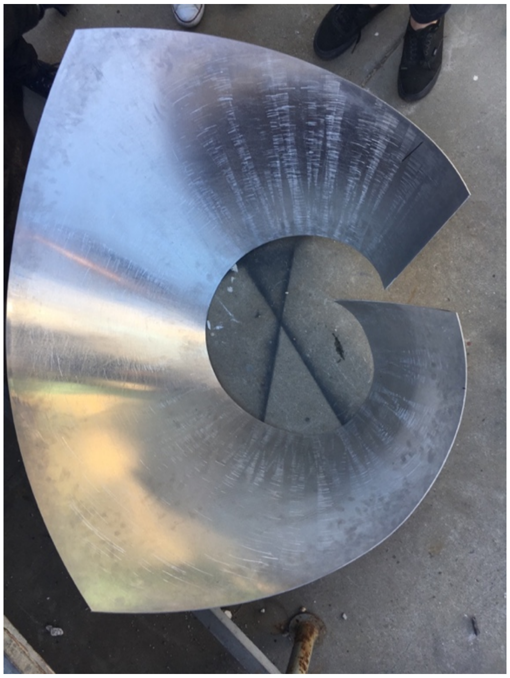

Fig. 7. Three Egg Whites, Soft Peaks after rolling and before gluing (Photo credit: John Lin)

The resulting truncated cone was epoxied along the overlapping seam, clamped, and left to cure for 12 hours. The application of epoxy to the overlapping seam was a success. After 12 hours, the epoxy, while not at full strength, was strong enough for the clamps to be removed. It would take another 12 hours for the epoxy to fully cure. In this instance, epoxy was a good way to join material due to its ability to remain hidden and stay true to the design (as opposed to mechanical fastening) and its relatively easy field application process (as opposed to TIG welding aluminum).

The chair was painted after the glue cured, and it has stood up well to normal use. There hasn’t been any explicit strength testing on the glued joint.

Fig. 8. Three Egg Whites, Soft Peaks (photo credit: Bennett Mueller)

Conclusions

Initial testing of the lab-made epoxy has shown promising results, providing sufficient mechanical strength for furniture. Our adhesive performed well in case study #3 and we feel confident about undertaking larger work with adhesives.

The failures of the epoxy in case study #1 were related to properties other than its strength, and in case study #2, the joint design was insufficiently resolved. Future work with adhesives and sheet metal will be limited to lap joints and metal will be formed by rolling or bending. The hydro-forming process described here was an interesting detour, and gave opportunity to collect material feedback about another type of adhesive (urethane) that we did not include in our project at the outset.

Performance of the lab-made epoxy could be improved by the addition of adhesion-promoting additives such as inert inorganic fillers, carbon nanotubes, carbon black, or ceramic nanoparticles, all of which have imparted adhesion improvements in similar studies, where the filled, over-the-counter adhesives show generally greater adhesion compared to the neat formulation.

Some potential challenges in using adhesives in construction remain, including their costs, questions about their effect on the life-cycle of otherwise recyclable materials, and their toxicity. More information on these characteristics of adhesives can be collected from further review of their use in other industries. In addition, more data about adhesives environmental performance is needed. Test standards exist to measure effects of humidity, temperature and UV radiation on adhesives joints. Moving forward, members of our team will further refine the parameters for field-applied, structural glues and continue to test at increased scale. Future adhesives selection parameters will include the two described in this project- suitability of application in the field and reasonable strength- and include two additional parameters- cost and impact on material life-cycles.

Student Researchers:

Ethan Kim
John Lin
Bennett Mueller
Mariana Puig Guijarro

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Notes:

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