AMERICAN INSTITUTE OF STEEL CONSTRUCTION

Structural Adhesives Workshop

MEETING NOTES AND PRESENTATIONS

Chicago, IL
August 13, 2019

Smarter.
Stronger.
Steel.

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1 Executive Summary

AISC and NSBA believe there is potential to better utilize materials such as adhesives (epoxies, glues, etc.) and chemical fillers within steel structures to give engineers and owners more tools to improve economics and potentially enhance reliability and robustness of a given structure or structural system. Further, we believe that these enhancements could be realized in both building and bridge structures assuming we are deliberate and informed when trying to utilize available products or specifying new ones.

This workshop was specifically setup to try and identify and quantify specific uses of adhesives and fillers for us in the structural steel industry. The impetus for the workshop stemmed from specifically from a Research Needs Statement (RNS) developed at a previous research innovations workshop that proposed the use of structural adhesives in steel bridge applications. AISC feels there is potential in both steel bridge and building applications. As such, some of the primary objectives of this workshop include:

1) Highlight potential uses of adhesives, fillers and other related materials as it pertain to bridges and buildings utilizing structural steel as their primary load resisting system
2) Examine historical and current research that has looked at using adhesives or similar materials within structural steel application
3) Determine the current state-of-the-art with respect to adhesives and similar products in both the general construction industry and other potentially relevant industries (automotive, aerospace, etc.)
4) Gain input from manufacturers regarding products that may already be available for our intended uses and what we, as an industry, may need to do to encourage further development of new products
5) Lay out an action plan to lay out next steps required to further develop potential systems and uses

This summary document provides a record of the Workshop and can be used as a reference for future work related to this endeavor.

2 Workshop Information

Date: Tuesday, August 13, 2019
Time: 8:00 AM – 5:00 PM CT
Location: Chicago, IL

2.1 Workshop Purpose

The purpose of this workshop is provide an open forum for the steel industry, adhesive manufacturers, asset owners, designers and researchers to discuss needs, real-world applications, and identify future research opportunities that will ultimately benefit the use of steel in both bridge and building markets and expand the market application of structural adhesives and sealers. The Agenda provided for this meeting is attached in Appendix A – Agenda.

2.2 Attendee Introductions

There were 19 people in attendance and each were individually introduced. See Appendix B – Attendees for a listing of attendees who were in attendance.

2.3 Tasks and Action Items

Task and action items from this meeting are noted throughout the document and summarized in Appendix C – Post-Meeting Tasks and Action Items.

3 Industry Overview, Needs and the Application of Adhesives

The workshop began with an overview of industry needs and possible applications for structural adhesives and fillers. Three distinct steel construction markets were discussed;

1) Steel bridges
2) Steel decking and cold formed steel
3) Commercial buildings (Discussed later in the day, but included in this section)

Prior to detailed discussions on the potential application of adhesives and fillers, some of the ideas the helped to initially spur the holding of the workshop were noted. These ideas include reducing bolting required for sealing on bridges, reduce number of bolts for strength, rehabilitation, and corrections of fabrication or construction defects.

3.1 Larry Kruth - AISC Position and Future Goals

Larry Kruth – AISC, reviewed the goals that AISC has for increasing the speed of fabricated and constructed for steel buildings and bridges. AISC has set a goal to reduce the time needed to design, fabricate and erect steel structures by 50% by 2025. Larry Kruth noted that a novel approach like the use of structural adhesives, is one of many options being evaluated a part of this initiative. This initiative will be formally announced on SteelDay on September 27.

3.2 Bridge Market Opportunities

Potential applications of adhesives and fillers within the steel bridge market were highlighted and discussed as noted below via two formal presentations.

3.2.1 Ronnie Medlock - Potential Steel Bridge Bolted Splice Market

Ronnie Medlock – High Steel Structures, discussed the potential market size for using structural adhesives in bridge application. By highlighting potential market opportunities, it is felt that commercial manufacturers will be more willing to participate in potential research studies and subsequently invest in targeting products to the structural steel industry. Ronnie specifically highlighted the surface area of connections in typical plate girder bridges that High Steel have fabricated to help demonstrate market potential. ***Ronnie Medlock estimates there is around 500,000 sq-ft of surface area that potentially can make use of structural adhesives for use in field splices on steel plate girder bridges within the United States.*** This estimate is based on using data from High Steel where it is assumed that High Steel represents approximately 10% of the steel plate girder fabrication market in the United States. .

The above assertion should be predicated by acknowledging that plate girder field connections only represent a portion of all of the various structure and connection types for the US steel bridge marker. For example, trusses, cable stay, deck arch bridge and built-up members also represent an opportunity for the application of structural adhesives. A more exact estimate that breaks out the different bridge and connection types that can potentially use structural adhesives should be created so that a more accurate view of the potential market can be created. Medlock estimates a potential 10 – 25% increase above the 500,000 sq-ft to include all other types of bridge applications. A similar exercise needs to be carried out for the commercial building market also.

3.2.2 Karl Frank - Application of Adhesive to Steel Bridge Construction

Karl Frank – NSBA Consultant discussed the application of adhesives in bolted field splices as a replacement for bolts, filler plates and gap filling. Based upon published shear strengths at elevated temperature (~200F), there are available toughened epoxies with shear strength equal to high strength bolts. The easiest application of adhesives is to develop fillers since the fill plates can be bonded in the shop. This would reduce the strength reduction that occurs when fillers are used. Karl noted that given the size of the material being connected, characteristics like ease of application and cure time would be important. Because of their continual exposure to the environment, unlike buildings, bridges are subject to corrosion in gaps, rust bleed and eventual pack rust. Bridge owners see steel as a large maintenance item and rust staining and pack rust at interfaces and gaps is often cited as a reason to not use steel. Fillers can reduce the maintenance costs overall and make steel a more appealing solution for highway bridge applications.

Karl Frank and Ronnie Medlock's presentations can be found in Appendix F - Presentations.

3.3 Tom Sputo - Potential Applications of Adhesives in Steel Deck Construction

Tom Sputo – Steel Deck Institute (SDI), discussed the typical construction of cold form steel decking used in building applications. Several potential applications were discussed that could utilize adhesives.

1) Cellular Deck Applications – Cellular deck is a product that consists of a traditional cold formed metal decking with a thin bottom plate attached to it. Traditionally, the bottom plate is attached with resistance spot welds. These welds can be seen from the underside of the deck, which would typically be the visible ceiling, and some architects do not like this for aesthetic reasons. Hence, there could be some potential in using adhesives to join the bottom plate to the deck in a cellular deck application.
2) Attachment Point for Decks to Supporting Members – Another potential use would be for attaching the steel decking to supporting members with adhesives. This would be in lieu of screws, power actuated fasteners or puddle welds.
3) Dry Floor System Application – The idea of a 'dry' floor system, a type of metal deck system that does not use concrete, used in steel buildings could also be an application where adhesives get utilized. This system could potentially use adhesives to bond gypcrete or similar type panels to metal decks in a dry system.

Tom Sputo's primary concern for using adhesives in building applications with metal deck is how adhesives would perform in a fire event. Fire resistance would need to be a key consideration when using adhesives in buildings and as such any research done should explicitly look at the issue and attempt to address it.

Similar to building applications, steel decking also has applicability as a modular bridge deck (as opposed to a traditional concrete deck) or as a short span bridge by itself. Steel decks offer the potential to speed up construction times significantly.

3.4 Gian (G.A.) Rassati - Application of Adhesives in Building Applications

G.A. Rassati - University of Cincinnati, has been performing research on behalf of ASIC in the area of bolted connections. He highlighted several possible uses of structural adhesives in commercial building applications. While there are natural overlaps between details and connections shared by building and bridge applications, we want to make sure that the special cases are not ignored.

3.4.1 Doubler plates in columns

G.A. Rassati highlighted one application that may lend itself to using adhesives would be in the attachment of doubler plates to column webs. The use of doubler plates in columns in a steel building are required to locally strengthen areas where localized demands can exceed available capacity in column webs, usually at rigid connections (moment). There is a significant cost associated with doubler plates due to welding requirements and accessibility when try to perform those welds. It is not uncommon for heavier columns than what is required to be specified to avoid using doubler plates.

The use of adhesives could be of benefit in doubler plate applications as the doubler plate itself would have a large surface area that could be bonded to the column web. In this application it would be desired to have a good combination of shear strength and workability of the material. Special consideration would likely be needed for fire protection where adhesives are applied due to relatively limited elevated temperature durability of adhesives/epoxies.

3.4.2 Stiffeners

Another potential use highlighted by G.A. Rassati was utilizing adhesives for attachment of stiffeners on steel members. In many cases, like doubler plates, stiffeners are required to resist localized high forces. The attachment of the stiffeners in these applications are most commonly achieved via fillet welds.

Attaching the stiffeners with adhesives could be a more cost-effective method then traditional welding techniques. Similar concerns to other building uses exist, primarily as it pertains to elevated temperature (fire) exposure.

3.4.3 Slip critical connections and Oversized Holes

The use of adhesives in combination with bolts in slip-critical connections could provide enhanced economy and behavior of the connection itself. The behavior may be enhanced due to a more uniform stress distribution in the connection via the adhesive bond. This enhancement to slip capacity was documented in the FHWA research mentioned previously.

In the case of bolted connections, oversized holes will lead to larger connections overall (i.e. more bolts), however the application of adhesives should be evaluated to determine if it would offset the additional bolts and achieve a more economical connection. These details are similar to those used on steel bridges and the group should look for cases where there is overlap so that limited research budgets can be better utilized without repeating work. Stadium roofs were proposed as an example where oversized holes have made erection easier, however they have had the drawback of creating very large traditional connections

3.4.4 Other Applications

Unlike bridges, building will typically have a façade which envelops the building and protects its contents and occupants from the external environment. Attachment of these facades is a natural candidate for the use of structural adhesives. Additionally, adhesives themselves can be evaluated as a thermal barrier between the interior and exterior of the building. However, one question that would need to be addressed would be the potential for thermal incompatibility.

3.5 Key Takeaways

Several potential applications of adhesives and fillers were highlighted in the steel building, steel bridges and steel decking sectors. These are summarized below

3.5.1 Steel Bridges

1) Adhesives in bolted field splices as a replacement for bolts and sealing of the connection
2) Chemical filler plates and gap filling to mitigate corrosion in gaps and rust bleeding

3.5.2 Steel Buildings

1) Adhesives for doubler plate applications that could be bonded to the column web
2) Adhesives for attachment of stiffeners on steel members
3) Adhesives in combination with bolts in slip-critical connections to provide enhanced economy and behavior of the connection itself by providing a more uniforms stress distribution in the connection.

3.5.3 Steel Decking

1) Adhesives in cellular deck applications to replace spot welds for attaching the bottom plate to the decking
2) Adhesives as attachment point for steel deck to supporting members
3) Adhesives to bond gypcrete or similar type panels to metal decks in a dry system..

4 Past and Present Day Research, Applications and Funding Opportunities

4.1 Justin Ocel and Robert Spragg - FHWA Past and Future Research Opportunities

Justin Ocel - FHWA highlighted to the group that the evaluation of structural adhesives is not something new and was previously studied several different research Projects in the 1980's-2000s for uses in bridges. Much of the previous work aimed to improve the fatigue life of crack prone cover plates. The FHWA report RD-84-037 from November 1987 entitled "Application of Adhesives to Steel Bridges" can be found at this link.

4.1.1 1980s FHWA Work

Justin Ocel first discussed FHWA funded work in the early to mid-1980s on the potential use of adhesives in steel bridge applications. There were 3 reports published with findings including (using FHWA numbering) FHWA-RD-84-037, FHWA-RD-86-037, and FHWA-RD-87-029. A suite of initial products were initially considered for this study, but three of the main adhesives selected for further testing; (1) Lord Versilok 204, (2) Dexter Hysol EA934, and (3) Dexter Hysol EA9309. A variety of mechanical properties and testing protocols were investigated for the adhesive products and their impact when used in conjunction with bolted connections. Parameters of interest included impacts on strength in both static and repeated loading (fatigue) scenarios and environmental impacts on the adhesives including creep testing.

4.1.1.1 Static Strength Testing (Report FHWA-c)

Static strength testing was done on various bolted connections supplemented with adhesives. It was found that adhesives did not increase the overall capacity of the connections, but they did increase the slip resistance of connections prior to the bolts going into bearing. This increase in slip resistance highlighted that in using adhesives with bolted connections on bridges it may be possible to eliminate slip checks in the design process.

4.1.1.2 Repeated Load/Fatigue Testing (Report FHWA-RD-84-037)

Fatigue testing showed a general increase in fatigue life when adhesives were used in conjunction with bolted connections. Similarly, when using adhesives to attach cover plates to girder along with limited bolting at the ends of the connection, fatigue life was also increased when compared to a welded cover plate.

4.1.1.3 Environment Testing Impacts/Creep (Report FHWA-RD-86-037and FHWA-RD-87-029)

Creep tests found that the adhesives were very sensitive to environmental conditions; temperature and humidity. These environmental conditions were further studied in bulk film tests where specimens are repeatedly strained and relaxed. Equilibrium of this process can take up to a year for a one-inch thick film. A worst case environment was chosen to be 120 F and 90% relative humidity based upon the results of the bulk film testing. Of the 22-epoxies and one acrylic, only two achieved equilibrium strength; 3M AF11 and Emerson Cuming Eccobond 91-9.

Rapid load testing was then performed with Emerson Cuming Eccobond 91-9 and American Cynamid FM-300. In these tests, changes in temperature did not really change strength, however humidity did. It was found that creep strength under dead load, rather than the rapid-loading strength under maximum load, would control the design of connections.

4.1.2 Early 2000s Work

Shield, Hajjar, and Nozaka studied the repair of fatigued steel bridge girders with carbon fiber strips (Shield et al 2003). Five different adhesives were used in the study and of those studied; 3M's DP-460NS was comparatively shown to have better ductility and was easier to apply. Testing in this program was unexpectedly expanded to include fire when arsonists damaged some of the test specimens. Out of plane distortion cracks were repaired by adhering angles to the connection. The bond of the repaired specimen was tested three years later with hammer blows and the repair did not break or fracture.

4.1.3 Current Work Being Initiated by FHWA

In 2018, Justin Ocel had Karl Frank submit a white paper outlining the application of structural adhesives as a supplement for shear, for the purposes of eliminating bolts and also filling gaps. Future studies would investigate shear behavior of toughened epoxies in bolted field bridge splices. Additionally, pourable epoxies are considered be a suitable candidate to fill the gaps that exist between two surfaces. At this time Ocel is looking to hire an engineer to assist with and perform testing to investigate the abovementioned parameters.

Initial shear testing will evaluate three epoxies under three different temperatures, three different humidity environments and at three thicknesses. The epoxies that are being planned to be evaluated are 3M DP460NS, Hysol EA9394, and Devcon HP250. "Steel grouting" will also be evaluated using Devcon Plastic Steel Putty (A), Stronghold MM1018 P, Stronghold MM1018 FL, and WR Meadows EG-96 HP. Again, a selection of temperatures and humidity ranges will be testing, along with varying levels of gap to be filled.

Based on discussion at the workshop, it was also noted that due consideration be given to the durability and performance of adhesives/fillers in high chloride environments. Similarly, the exposed edges of any adhesive or grout must be evaluated for long term performance.

4.1.4 Key Takeaway and/or Action Items

The previous work done by FHWA provides valuable data points and considerations for any future studies that are done in looking at applications of adhesives and/or fillers in steel construction. ***Action: AISC and NSBA will stay involved with the FHWA research project as it progresses and ensure any research efforts funded by AISC/NSBA are not unnecessarily duplicating efforts as it relates to trying to bring products to market***.

4.2 Robert Kogler and Laura Erickson - Lessons Learned from Testing Structural Adhesives

Robert Kogler and Laura Erickson - Rampart, typically performs corrosion studies for the US Navy, however they have been looking at adhesives to adhere non-metallic objects to steel – some of which having a thermally applied coating. Applications investigated include both new construction and repair. They have also been evaluating adhesives in high chloride environments, cure times for faster construction, and hybrid connections that include adhesives and bolts for redundancy of the connection. Some key items and considerations their studies have shown include:

1. Surface preparation is important,
2. Bond line thickness consistency can affect performance (use beads as spacers),
3. Method of adhesive curing can change cure times,
4. Large or inconsistent gaps between surfaces is important to control,
5. The addition of reinforcing fibers can change performance,

6. Repair and inspection can be a challenge in the field.

Robert Kogler has drafted a set of requirements for the use of adhesives. These account for environmental exposure, long-term durability, strength, bond between different surfaces (e.g. painted and not painted), and curing method and time.

The Navy has performed a lot of modeling and study which may be useful to our structural adhesive initiative. Robert can assist with making necessary introductions if that will help move the process along and prevent studying the same things over again.

4.2.1 Key Takeaway and/or Action Items

Kogler and Erickson have done a large amount of work related to adhesives in conjunction with the US Navy. Some or much of this work could be applicable to this current initiative. ***Action: Robert Kogler will share whatever relevant data and information he has based on his work with the Navy. This will help in identifying products that may not be readily known by others within this group.***

4.3 Academic Research with Adhesives

4.3.1 Caroline Bennett - Adhesives in Steel Bridge Fatigue Applications

Caroline Bennett – University of Kansas, presented research she has overseen that compared the use of adhesives versus mechanical fasteners and welding in retrofitting steel bridges that had experienced fatigue damage (i.e. cracking).. A few different studies were highlighted including studies looking at bonding plates to tension flanges of girders to applications on cross framing connections where distortion-induced fatigue was problematic. Her work highlighted both the advantages and challenges when using adhesives in this application.

One parameter Caroline Bennett studied was the effects of varying thicknesses of adhesively bonded overlays. Testing showed that, somewhat surprisingly and conversely to model predictions, there was not a strong correlation between bond thickness and de-bonding frequency of the overlays.

Bennett's research also included monotonic peel tests with different configurations of adhesive types, thicknesses and bonded joints that included 'breather cloth' (filter fabric) within them. These tests showed that bonded areas with thin adhesive layers did not generally exhibit much benefit from polyester breather cloths. However, they did show more of an impact when thicker layers of adhesives were being utilized.

Testing was also performed on carbon fiber reinforced polymer composites (CFRP) overlay doublers that were adhesively bonded to steel plate. These test showed very good results.

Mitigating the effects of distortion induced fatigue of cross-frame connections with different applications of epoxies and CFRPs were also investigated and tested in some of Caroline Bennett's research. A hybrid bolted and layered CRFP connection and a composite block were evaluated. Both may be suitable repair procedures with the block method possibly being easier to construct in the field. In the case of the block, West System 105 Epoxy Resin and 206 Slow Hardener with glass cloth were used and shown to perform well; these are comparable to what is used to repair boats. Additional block configurations tested included carbon fibers which also performed well.

Caroline Bennett also shared a listing of adhesives/epoxy products she had either tested or knew of from literature reviews. This data is extremely helpful and will be the starting point when trying to determine optimal performance properties and specifying products to look at for the current endeavor. ***Action: Caroline Bennett to provide a listing of known adhesives and other similar products that have been used in various applications to date that she has encountered. She will share this with the workshop attendees***.

4.3.2 Matthew Hebdon - CFRP Reinforcing of Corroded Steel Beams

Matthew Hebdon – Virginia Polytechnic Institute Tech, presented research he has been performing for Virginia DOT on the strengthening of existing steel structures by applying carbon fiber reinforced polymer composites (CFRP) with structural adhesives. The primary goals of his work are restoration of corroded/damaged and increasing the carrying capacity of steel girders.

Matthew Hebdon's testing has studied the failure modes and overall performance of CFRP applied to the bottom flanges of steel beams. Failure modes have included rupture of the attachment, intermediate debonding and end debonding. A possible solution for the end debonding case has been the introduction of bolts at the ends of the attachment. Although, Matt has only looked at the adhesion of CRFP, his studies and their results likely have similar application in the adhesion of steel to steel. Future research will look into adhesion of the CFRP to non-uniform surfaces (i.e. corroded), the durability of the attachment and live load testing.

Action: AISC and NSBA will continue to follow Matthew Hebdon's research related to CFRPs and see ensure we are staying apprised of relevant results of the work.

4.4 Research Support

Before any adhesives or similar products can be put into practice, existing information will need to be synthesized and additional research performed. There are several means of funding research, the agencies noted below only represent two possible avenues.

4.4.1 Domenic Coletti - Transportation Research Funding Methods

Domenic Coletti - HDR is currently the chair for the Transportation Research Board AFF20 Committee on Steel Bridges. Part of this committee charge is the assessment and promotion of research needs statements in the area of steel bridges. Research that the group often receives or request is specifically intended to address immediate needs of the state departments of transportation. Domenic Coletti reviewed the methods by which this research is typically funded (e.g. Federal Highway Administration, individual states or by a pooling of funds among several states to address a common need). A research needs statement on the application of structural adhesives in steel bridges was submitted to AFF20 and can be found in Appendix E – Highway Bridge Research Needs Statement.

4.4.2 Devin Huber - AISC Committee on Research

Devin Huber - AISC reviewed the process by which research is chosen and eventually funded by AISC. Devin authored an article for the September 2019 edition of Modern Steel Construction that explains the history, process and importance of research to AISC and the steel industry. Generally, ASIC has $1-million plus allocated toward ongoing research, however there are instances where partnerships are formed where groups with similar needs pool their funds to solve a common issue. Research typically takes two forms, research devoted to addressing issues and updates to the specification, and research looking into innovation. Devin and the AISC Committee on Research will play a significant role in moving the study of structural adhesives in steel applications forward.

5 Adhesive Manufacturer Input

Direct involvement by adhesive and sealant manufactures is paramount to the successful evaluation and usage their products in structural steel applications. The workshop had difficulty attracting participants from various large manufacturers. Initially 3M had agreed to attend, however they later backed-out just prior to the workshop. Sika was a last minute addition to the agenda.

5.1 Aamer Syed - Sika Corporation

Due to a prior commitment, Aamer Syed – Sika, was only able to attend the first half of the workshop. Sika is a chemical company with seven target markets, one is sealing and bonding - for steel, concrete, etc. They are a pioneer in the use of epoxy in construction and is globally one of the biggest suppliers of epoxy. However, they are not just an epoxy company. Aamer Syed compared the needs discussed at this workshop with those in the construction of wind turbine blades.

Aamer Syed recommended that the group consider developing a parallel to the ASTM C881/C881M Standard Specification for Epoxy-Resin-Base Bonding Systems for Concrete. This specification describes 8 types of applications where each has its own target properties. An example of bridge application is the type 7 epoxy used in segmental bridges connections. It should be noted that the epoxy used in segmental bridges does not serve a structural purpose and is intended as weatherproofing/sealing. The ASTM specification would act as a means of qualifying a spectrum of epoxies and fillers which commercial products can be certified as meeting. For example, viscosity limits for a specific application. The group should consider developing a strawman equivalent to the C881 for steel construction. Workshop attendees, had concerns about the speed with which such a standard could be developed. While it is not a significant concern when using epoxies and fillers in commercial applications, State Transportation Departments (DOT) cannot require a specific product or one that is considered proprietary. So, a specification will need to be developed whether it is an ASTM specification or an AASHTO/NSBA Steel Bridge Collaboration document. Vendors would eventually certify their products to one of these ASTM standards so that the right epoxies would be used for the right application.

Aamer Syed stated that epoxies that have a high modulus will be brittle. This high modulus can be lowered so that the epoxies are more flexible; however, these are not typically used in structural applications.

It was recommended that the group categorize the different anticipated applications, then define the properties needed, and then challenge the suppliers. Long term durability is key and will need to be evaluated with test such as freeze-thaw testing, thermal compatibility comparisons and chloride testing.

Ease of application in the shop and field will be key to controlling quality and cost. While epoxies are typically applied with a trowel, they can be sprayed and injected. It was suggested that a compressible (like a double sided tape) would be beneficial and make connecting very large components easier.

Aamer Syed reinforced the importance of manufacturers like Sika to understand the potential size of the market. Information similar to what Ronnie Medlock presented is a start, however should be expanded to capture other bridge types and connection. Also, an estimated potential for use in the commercial building market also need to be developed. Both estimates will improve the likelihood of support and engagement by adhesive manufacturers.

The group should also follow-up with Sika representative, Bernie Borchard.

Action: Performance standards and requirements will be established for various applications of adhesives/fillers. In doing this it may be found that existing products already exist that could be utilized or new products may need to be produced to fit these requirements.

5.2 Larry Grimenstein - Stronghold Coating Ltd.

Larry Grimenstein is a chemist and owner of Strong Hold (www.strongholdone.com) who is a manufacturer of sealers for thermal spray, aluminum castings and naval ship applications. Larry Grimenstein is also affiliated with "Diamant - The Metroplastic Company" located in German. He currently manufactures their product in the United States and still continues to do sealer research.

Diamant has a liquid grouting compound call MM1018. "MM1018 provides high compressive and shear strength, as well as 100% volume restoration inside the gap between bearing and construction. It offers high dimensional stability, with insignificant shrinkage. Mechanical machining of face and back plates is not needed."

This product is intended to fill the gaps up to 140 mm in size that typically resulting from tolerances, welding distortion, design errors, assembly imprecision, and etc. between two adjoining surfaces. MM1018 can be applied as a two part liquid and as a putty. It is a proprietary product that has been approved for use in various countries.

An example applications shown was the correction of a misaligned bridge finger joint where MM1018 was used as a beading material to level and adhere the finger joints. MM1018 was also used on the Gerald Desmond Bridge.

MM1018 seems to address the maintenance issues with steel interfaces where often rust develops and staining and pack rust result. Bridge owners cite lifecycle cost and maintenance of steel due to corrosion as a significant barrier to its use when compared to concrete.

MM1018 is a proprietary product and would not be specified "as-is" on any state transportation project.

6 Additional General Notes

Several concerns were discussed throughout the day which need to be researched, and addressed before adhesives and fillers would be allowed for use in structural applications. Environmental concerns are most significant with highway bridge applications given the continual exposure to things like chlorides from deicing salts, and humidity. Testing of adhesives and defining classifications of adhesives would need to consider chloride, ultraviolet and freeze/thaw exposure.

In commercial building applications, fire protection and flammability were considered the most important concern to address. However, steel will require fireproofing regardless, so an economic analysis of specifying additional fire protection, in the case of flowing systems, might need to be performed to ensure there is a net gain in economy for steel.

Application of adhesives on large structural members comes with its own challenges. The work plane orientation where the adhesives are being applied can be above a person's head (e.g. the underside of a steel beam). In these instances and different cases, cure time becomes concern; slow cure versus fast cure.

Long-term durability of adhesives needs to be understood as many of the applications are permanent and rehabilitation while in-service would be very difficult and challenging. Replacing bolts in a field splice is not impossible, however if a connection which constructed of adhesives needed to be rehabilitated because the longevity of the product is inadequate, it would diminish the benefits.

In some applications, like beam cover plates, a combination of adhesives and bolts may be beneficial to counteract the prying of the adhesive from the ends inward. Again, an economic analysis should be performed to ensure that the introduction of adhesives makes the steel option more cost effective than a concrete structure.

Exceptionally tight fabrication and construction tolerances are a common issue cited by fabricators which has need said to add cost without significant benefit; steel structures are often compared to "Swiss watches" as both are held to high precision. The injection of adhesives or fillers could address any loosening of tolerances. For example, oversized holes with air space injected with structural filler.

Fill plates are often necessary when a bolted connection occurs at a location where the thickness of the two connected member changes. Structural adhesives may be a suitable replacement for steel fill plates used in these types of connections. In the case of a bolted field splice, once the bolts slip and go into bearing, the fill plate must be developed to distribute the total stress uniformly over the combined section of the member and the fill plate. In these cases where the fill plate is ¼ in or thicker (for example in a highway bridge), a reduction factor to be applied to the bolt shear strength for fill plates which can result in an increase in the number of bolts required for the connection. Eliminating the fill plate and replacing it with structural adhesives may reduce fabrication cost and also the need for additional bolts.

The attendees of the workshop should develop a comprehensive list of the applications of structural adhesives for both bridge and building applications. With each application, an explanation would be necessary to describe the application and how it makes steel quicker or more economical when compared to concrete or timber. For example, in the case of bolted splices, reducing the number of bolts reduces the time and cost to fabricate make the connection in the field. However, where is the break point where the deduction in bolts offsets the cost of the adhesive and its application?

Some time was spent focusing on sealing, bedding and grouting between surfaces. While companies like Stronghold are able to demonstrate the application in the field and how it leads to a more maintainable structure by eliminating water infiltration, bleeding and pack rust, does it make steel a more appealing and competitive option to owners based on first time costs and time to construct. Certainly for bridge owners that struggle with maintenance of their assets, the elimination of a very common problem with steel structures would take away a significant argument for not using steel.

For each of the applications identified, a specification/procedure outlining the application in each instance should be developed. Similar to weld procedure, there are many that are common which should only need to be written once, approved once and reused many times. The same can be said about the typical applications of structural adhesives. Before any application of adhesives was to “go to market” an application specification/procedure should also be developed and approved. For bridge applications, the AASHTO/NSBA Steel Bridge Collaboration as a mechanism for this.

A baseline or the characteristics and capabilities of existing off the shelf adhesives should be the first step. This work has already been started at University of Kansas. However, it may need to be more formalized and comprehensive. Once this work is completed, it should be the guide to all of the adhesives that would have application in bridge and buildings. Once an application is being evaluated (e.g. connecting doubler plates in columns), the researcher assigned to the project should not be re-evaluating the properties of the available adhesives. Rather they should already know which they are going to test with.

Adhesives are being used extensively within the automotive and aerospace industries. AISI currently has a group devoted towards the use of steel in automotive applications who also have experience in the application of adhesives. It may be valuable to set aside some time to discuss the needs presented at this workshop with them. Robert Wills – AISI can be an intermediate point of contact within AISI.

7 Next Steps

The following outlines some of the next steps in furthering this initiative.

There are three classes of problems that we hope to address:

1. Adhesives for connections:
    - 1.1. Economics of hybrid connections.
        - 1.1.1. First do an RNS and identify connections that people would likely to approve.
        - 1.1.2. Address design - how do you design?
            - 1.1.2.1. Oversize holes.
            - 1.1.2.2. No fill reduction.
        - 1.1.3. Cannot design until we test?
    - 1.2. Decking
        - 1.2.1. SDII-like task that should reach into the auto industry (although they don't have the fire problem); their key is to save weight and they have experience in adhesives.
        - 1.2.2. Short span orthotropic, however as a type of "steel cardboard".
    - 1.3. Doubler Plates and Stiffeners
        - 1.3.1. Mike Culmo at CME has been working on a project and may be a source of information.
        - 1.3.2. Maybe start with building applications and migrate to bridges.
    - 1.4. Investigate doubler plate attachment as a solution to a common commercial building issue.
2. Fill for new construction
    - 2.1. Evaluate products like Stronghold MM1018.
    - 2.2. Develop an AASHTO/NSBA Steel Bridge Collaboration document.
    - 2.3. Study the economics of a hybrid connections.
3. Something is the middle that both can act as an adhesive and as a filler.
    - 3.1. Consider for strengthening in rehab situations.
    - 3.2. Similar to beam end repairs.
    - 3.3. Adhesively bonded steel repairs.

Need a list of who has used what for various applications. Caroline Bennett provided the group with an initial listing of adhesives and their properties. This should be further developed and specifications for each application should be developed.

Explore a possible synergy with the Navy through the Robert Kogler. The Navy may be willing to share past studies which may eliminate the need to repeat work that has already been performed. Larry Grimenstein may also be a possible source of relevant contacts.

8 Appendix A – Agenda

Structural Adhesives Workshop
AISC Headquarters
130 East Randolph, Suite 2000
Chicago, IL, 60601

Background and Purpose: The use of structural adhesives and fillers in steel bridge and building applications offers several opportunities to lower overall costs and improve competitiveness. Although their use has become commonplace in other industries, their application in the steel bridge and building markets has not been pursued to any great degree.

The purpose of this workshop is provide an open forum for the steel industry, adhesive manufacturers, asset owners, designers and researchers to discuss needs, real-world application, and identify future research opportunities that will ultimately benefit the use of steel in both bridge and building markets and expand the market application of structural adhesives and sealers.

Meeting Agenda - Tuesday, August 13 (8:00 am to 5:00 pm)*

1. Attendee Introductions - All (8:00 am – 8:15 am)
2. Industry Overview, Needs and the Application of Adhesives (8:15 am – 9:15 am)
    a. Bridge Market: Frank/Medlock – NSBA/High Steel
    b. Building Market: Kruth – AISC
    c. Steel Decking: Sputo – SDI
3. FHWA Past and Future Research Opportunities: Justin Ocel and Robert Spragg – FHWA (9:15 am – 10:00 am)
4. Break (10:00 am – 10:15 am)
5. Adhesive Manufacturer Input: Aamer Syed – Sika - US (10:15 am – 10:45 am)
6. Structural Adhesives Experiences and Lessons Learned: Robert Kogler and Laura Erickson – Rampart, LLC (10:45 am – 11:30 am)
7. Lunch (11:30 am – 12:30 pm)
8. Adhesives in Bridge Fatigue Applications: Caroline Bennett – University of Kansas (12:30 pm – 1:15 pm)

9. CFRP Strengthening of Corroded Steel Bridge Girders for Flexure: Matthew Hebdon – Virginia Tech (1:15 pm – 2:00 pm)
10. Research Support (2:00 pm – 2:30 pm)
    a. Transportation Research Funding Methods: Domenic Coletti - HDR
    b. AISC Committee on Research: Devin Huber - AISC
11. Break (2:30 pm – 3:00 pm)
12. Adhesive Manufacturer Input: Larry Grimenstein – Stronghold (3:00 pm – 3:45 pm)
13. Next Steps (3:45 pm – 5:00 pm)
    a. Discuss the needs for further research and support.
    b. Identify possible experimental real-world application.
    c. Discuss pursuing the use of sealers versus adhesives or both.
    d. Discuss the future formation of a steering committee.
14. Adjourn

* Note: Agenda reflects actual day's meeting schedule which was adjusted to accommodate speaker commitments elsewhere.

9 Appendix B – Attendees

Last Name	First Name	Company	Email	Industry
Bennett	Caroline	University of Kansas	crb@ku.edu	Academic
Coletti	Domenic	HDR	Domenic.Coletti@hdrinc.com	Bridge Engineer
Erickson	Laura	Rampart, LLC	lauraerickson4@gmail.com	Consultant
Frank	Karl	NSBA - Consultant	karl.frank@engr.utexas.edu	Trade Organization
Garrell	Chris	NSBA	garrell@steelbridges.org	Trade Organization
Grimenstein	Larry	Strong Hold	strongholdone@cs.com	Manufacturer
Hebdon	Mathew	Virginia Tech	mhebdon@vt.edu	Academic
Huber	Devin	AISC	huber@aisc.org	Trade Organization
Kogler	Bob	Rampart, LLC	bobkogler@verizon.net	Consultant
Kruth	Larry	AISC	kruth@aisc.org	Trade Organization
Medlock	Ronnie	High Steel Structures	rmedlock@high.net	Bridge Fabricator
Ocel	Justin	FHWA	Justin.Ocel@dot.gov	Federal Agency
Rassati	Gian (G.A.)	University of Cincinnati	RASSATGA@ucmail.uc.edu	Academic
Russo	Frank	Michael Baker International	FRusso@mbakerintl.com	Bridge Engineer
Spragg	Robert	FHWA	robert.spragg@dot.gov	Federal Agency
Sputo	Thomas	Steel Deck Institute	tsputo50@gmail.com	Trade Organization
Syed	Aamer	Sika	syed.aamer@us.sika.com	Manufacturer
Wills	Robert	AISI	rwills@steel.org	Trade Organization
Wisch	Gary	DeLongs inc.	garyw@delongsinc.com	Bridge Fabricator

10 Appendix C – Post-Meeting Tasks and Action Items

Please note that these actions are currently based on what was discussed at the Workshop. Further actions will likely come forward as items are worked on and progressed. A centralized 'live' version will be shared with attendees to reference.

<u>Item – Adhesives 1</u>
Description: **Setup of a centralized information sharing location – Google Drive or Similar**
Assigned To: Chris Garrell
References/Attachments:
Action/Work Items Chris Garrell will setup a shared drive, Google Drive or similar, where information related to potential use of adhesives, fillers, etc. can be shared.
Target Date for Completion September 15, 2019
Status Updates

<u>Item – Adhesives 2</u>
Description: **Development of an Existing Product Listing/Database**
Assigned To: Chris Garrell and Caroline Bennet will lead effort and obtain relevant information from attendees as needed.
References/Attachments:
Action/Work Items (1) Caroline Bennett to provide a listing of known adhesives and other similar products that have been used in various applications to date that she has encountered. She will share this with the workshop attendees. (2) Meeting attendees will add any products they may be familiar with to this list. This includes products looked at in Kogler's work with the Navy

Target Date for Completion
October 15, 2019

Status Updates

<u>Item – Adhesives 3</u>

Description:
Develop performance objectives for specific applications of adhesives/fillers and identify existing products that could be considered. (May need to develop a type of ASTM C881 specification if existing products do not suffice)

Assigned To:
Chris Garrell and Devin Huber

References/Attachments:

Action/Work Items
Garrell and Huber to work with groups noted below to put performance objectives together for bridges and buildings, respectively.
Bridge Group – Bennett, Hebdon, Garrell, Medlock, Frank (connections, fillers, retrofit)
Buildings Group – Rassatti, Kara Peterman, Huber (Doubler and stiffeners, fillers, facades/others)

Target Date for Completion
November 15, 2019

Status Updates

<u>Item – Adhesives 4</u>

Description:
Develop Initial Research Needs Statement based on Workshop Input and Feedback

Assigned To:
Chris Garrell, Devin Huber and Ronnie Medlock will own the item but will solicit feedback from workshop participants

References/Attachments:

Action/Work Items
Develop a Research Needs Statement (RNS) for the use of adhesives/epoxies with connections including bridge and building applications. Try to avoid duplicating efforts of FHWA study.

Target Date for Completion
November 15, 2019

Status Updates

Item – Adhesives 5

Description:
Ongoing involvement with planned FHWA Research and other University Research (Hebdon, Bennett, etc.)

Assigned To:
Chris Garrell

References/Attachments:

Action/Work Items
AISC/NSBA to stay apprised of FHWA research efforts on adhesives and ensure any parallel work is not duplicating their efforts. Similarly, efforts will be made to stay aware of other academic research ongoing in adhesives.

Target Date for Completion
Ongoing

Status Updates

Item – Adhesives 6

Description:
Metal Deck Initiatives with Adhesives

Assigned To:
Tom Sputo

References/Attachments:

Action/Work Items Tom Sputo to work with Robert Wills and others to see if an initiative can get kicked off for metal deck applications. It is envisioned this would be similar to the Steel Diaphragm Innovation Initiative (SDII).
Target Date for Completion TBD
Status Updates

11 Appendix D – Individual Attendee Notes

Exploring Adhesives for Steel Bridges - Medlock

1) Have RNS from May 2018 AISC Research Innovations Workshop; idea originated at the February innovations meeting in Chicago from Ted Zoli
2) Joint technical issue with buildings / vertical construction
3) Workshop in Chicago, 13 August 2019
   a) Having trouble getting vendors
      i) Stronghold is on board
      ii) 3M backed out
      iii) Have not heard from Sika
4) Potential benefits
   a) Reduce bolt sealing
   b) Reduce number of bolts
   c) Rehabilitation
   d) Corrections for fabrication or construction defects
5) Workshop in Chicago, 13 August 2019
   a) Attendance: Gary Wisch; Chris Garrell; Larry Grimenstein, strongholdone@cs.com, 937.704,4020 ?, Stronghold; Domenic Coletti; Caroline Bennett; Devin Huber; Robert Spragg (FHWA); Bob Kogler, Rampart; Laura ?, Rampart; Matt Hebdon; Ronnie, Larry Kruth, Gaio? R?, Tom Sputo (metal deck guy), Frank Russo, Justin Ocel, Robert Wills, Aamer Syed, Sika
   b) Ronnie: I girder connection annual SF might be half million; all connections may be 10% to 25% higher
   c) Karl Frank
      i) Can adhesives help us with durability? Seal things / connections etc
      ii) Bridge connections will not get to the yield loads that you'll get in structural connections
   d) Tom: consider deck opportunities
   e) Sika, Aamer Syed, syed.aamer@us.sika.com
      i) Sika is a chemical company, seven target markets, one is sealing and bonding - for steel, concrete, etc.
         (1) Pioneer in the use of epoxy in construction and is the biggest supplier
         (2) However, not just an epoxy company
      ii) Wind turbine blades may be similar; epoxy is used; 7-8 years now
         (1) This is a structural connection
         (2) Note that in a segmental bridge the epoxy is not structural; it is waterproofing / sealing
      iii) ASTM C881 - classifies epoxies for certain applications; eight types
         (1) Targets - shear, compression, modulus, etc
         (2) Applications
         (3) Rigid and flexible
         (4) Vendors certify their products to these types
         (5) Epoxies that are high modulus will be brittle; connection must be very rigid

(a) Can get lower modulus epoxies with more flexibility; however, these are not structural

iv) Recommends
(1) Categorize applications, then
(2) Define the properties needed, and then
(3) Challenge the suppliers

v) Long term durability?
(1) Good question
(2) Can validate through testing
(a) Freeze-thaw testing is done
(b) Thermal compatibility
(c) Salt testing

vi) Application (question) - can be sprayed?
(1) Often troweled on
(2) Can be sprayed
(3) Can be injected

vii) Should we look beyond epoxy
(1) Will depend on design
(2) But high modulus means epoxy

viii) Bernie Borchard? Sika's guy who is always looking for new uses for epoxy

f) Justin Ocel, FHWA research

i) Pedro's study
(1) Attachments to the tension flange of a w shape
(2) Beam specimens
(3) From tension tests, found that it was not possible to increase tension capacity, but can improve slip
(a) Perhaps we could get rid of the slip check if we use epoxy
(4) From creep tests, found big environmental (daily temp) effect
(5) Bulk film test
(a) Strain and relax - defines "equilibrium strength"; can take up to a year for a one-inch thick film to reach equilibrium
(b) Worst case environment - looked at highs, record highs and R/H %s; choose 120 degrees F, 90% R/H
(c) Of 23 submittals, only two could develop the equilibrium strength: 1) 3M AF11, 2) Emmerson Ecobond 91-9
(6) Next round - 91-9 and Cyanmid ?
(a) Rapid Load Shear Test - Changes in temperature don't really change strength, but humidities do
(b) Creep test - found pretty big hit
(c) Key finding - creep test under dead load will control

ii) U Minnesota
(1) Shield, Hajjar, Nozaka - repair of fatigued steel with carbon fiber strips

(2) Hu, Shield, ?, ? - 3M adhesive for distortion induced fatigue cracks (loading dock on fire study)
(a) Angle fix - glued angles on; tested three years later with a hammer; still "good"
(b) Strength reduction due to factors
(i) Fire (of course) hugh problem
(ii) Immersion in tap water / with high temps was bad
(iii) Etc
iii) 2018 - white paper from Karl
(1) Reduce number of bolts? Fill gaps?
iv) Shear testing - Robert Spragg with Justin
(1) Looking for an engineer with a work plan; then will go
(2) Variables for one
(a) Three epoxies
(b) Three humidities
(c) Temp from -30 F to 140 F
(d) Thicknesses - 5 mil, 15 mil, snug tight
(e) Shot blast to SP 6
(f) Tension bolt at testing?
(3) Variable for steel grout testing
(a) 10 min loading rate
(b) Larger test diameter, etc.
(c) Four epoxies
(d) Three humidities
(e) Room temp to 140 F
(f) Thicknesses - ¼", ⅜", ½"
v) Comment from Larry
(1) Need to consider durability, performance to salt water
(2) Humidity will only affect the outside edges
g) Bob Kogler, Rampart
i) Generally does corrosion and paint for the Navy
ii) Having been looking at adhesives to adhere non-metallics to steel
iii) Some new construction, some for repair
iv) Values
(1) Seawater, warm seawater
(2) Faster construction - gone to cure times of a few hours
(3) Sometimes with fasteners, sometimes not
v) Blasted steel
vi) See 20 to 25 years in seawater
vii) Creep has been a discriminator - some long lasting paint under load fail quickly; but some succeed
viii) Peel testing - measured in pounds per linear inch (pli)
ix) The Navy's primary sealant is a polysulphide

x) Need to be mindful about inspection as well
xi) Surface prep
xii) Bob has draft requirements
xiii) Navy does a lot of modeling - an energy model / fracture mechanics model

h) Caroline Bennett
  i) Discussed advantages v mechanical fasteners as well as advantages v. welding
  ii) Adhesively bonded overlays
    (1) Looked at bending fatigue
    (2) Various thicknesses, up to ¼”
    (3) Did not find a strong correlation between bond thickness and debond frequency (contrary to model prediction)
    (4) Monotonic peel tests
      (a) Did better with breather cloth (filter fabric)
      (b) Strength reduced with increase in thickness, though less-so when cloth was used
      (c) For very thin bonds, presence of breather cloth had negligible impact
    (5) CFRP doublers adhered to steel plate - very good results
    (6) Distortion induced fatigue - adhesively bonded overlays
      (a) Tried cheap resin - two part West - like you’d use for a boat - did well
      (b) Tried different materials - glass cloth w/ West - debonded; chopped fibers w/ West - did well

i) Matt Hebdon
  i) Work for VDOT - have steel bridges with wooden decks - lots of corrosion
  ii) Addressing capacity to flanges
    (1) Strengthening to address losses to corrosion
    (2) Taking yet further for new high loads
  iii) Beam tests
    (1) Three CFRP solutions - one layer on bottom of BF, two layers on bottom of BF, one layer on top of BF
    (2) Two products - Sika, Nippon - chosen by DOT
    (3) Results
      (a) All added capacity
      (b) Ductility based on the CFRP strain limits
      (c) Multiple layers not additive
  iv) Small scale tests
    (1) Double-strap joint specimens - seeing minimal impact on adhesion from corrosion
  v) Testing continues
  vi) Will look at prep other than blasting - maybe needle gun

j) Gian A. (Sounds like “John”; also goes by G.A.)
  i) University of Cincinnati
  ii) Have been doing tests on doubler plates
  iii) Fabricators say they would rather increase the section than weld-on a doubler plate; so consider using an adhesive

iv) Consider for installing stiffeners? Maybe where you are looking to develop tension field action
    (1) Probably don't need a lot of adhesion - these work with tack welds, for example
v) Filler plates?
    (1) More even distribution of stress? Would help design assumptions
vi) Thermal brakes - maybe structural adhesives would work for this; use as an insulating material
vii) Improvement of slip critical connections - as Caroline said, it would give you more uniform stress distribution
viii) Composite action - use instead of studs to attached building floor
ix) Is strain compatibility a concern?
x) Temperature ranges and humidity changes in buildings would be more controlled than for bridges
xi) Other question marks
    (1) Creep behavior
    (2) Fire resistance
xii) Comment from Karl - Facilitate oversize holes? Maybe on a stadium roof? Fabricators sometimes increase holes size to facilitate fit-up but then pay a design penalty; maybe the penalty could be avoided with the addition of adhesive
xiii) Tom (floor guy) - emphasized potential issue of fire; fire resistance is a key safety advantage for steel over timber

k) Domenic and Devon discussed TRB and Devon AISC
l) Larry
    i) Research chemist; had one liquid spray shop
    ii) Started working on sealers; now a major manufacturer of sealers
        (1) For thermal spray
        (2) For aluminum castings
        (3) Non-solvent sealers
        (4) Government materials
    iii) Also with Diamant, The Metroplastic Company - German; Larry manufactures their product in the US; still do sealer research
    iv) MM1018 - liquid shim
    v) Almost everything you put together has a gap somewhere - tolerances, welding distortion, design errors, assembly imprecision, etc.
    vi) Comes in two versions
        (1) Liquid, two part
            (a) Approved by various countries
            (b) Max gap is 140 mm (abz? up to 10 mm)
            (c) How long to cure? 24 hours to bolt
        (2) Putty
            (a) Good for very large parts
            (b) How clean?

vii) Large expansion joint for DS Brown
 (1) 1018 facilitates alignment
 (2) Used on Gerald Desmond bridge

m) Next Steps
 i) Chris will compile notes
 ii) Three classes of problems
  (1) Adhesives for connections
   (a) Economics of hybrid connections
    (i) First do an RNS
     1. Identify connections that people would like to approve
    (ii) Address design - how do you design?
     1. Oversize holes
     2. No fill reduction
    (iii) Can't design until we test?
   (b) Decking
    (i) SDII-like task
     1. Should reach into the auto industry (although they don't have the fire problem); their key is to save weight
    (ii) Short span orthotropic
     1. Steel cardboard - may
   (c) Stiffeners
    (i) Mike Culmo is doing a project
    (ii) Start with buildings and migrate to bridges
   (d) Doubler plate
    (i) Building issue
  (2) Fill for new construction
   (a) Test MM1018
   (b) Write Collaboration spec
   (c) Economics of a hybrid connection
  (3) Something is the middle that fills and sticks
   (a) For strengthening in rehab situations
   (b) Like in a beam end repair
   (c) Adhesively bonded steel repairs
  (4) Need a list of who has used what for various applications
   (a) Caroline's list is a start
   (b) Need a spec for each application
  (5) Explore synergy with the Navy through the CAG - Bob is our guy; Larry G. will talk to Bob Brown too
  (6) Tom will talk to Robert W. re a reasonable path forward to the deck stuff using cold form; cold form is in the middle of October

12 Appendix E – Highway Bridge Research Needs Statement

RESEARCH NEEDS PROBLEM STATEMENT

TITLE

2019-01: Application of Adhesives in Steel Bridges

BACKGROUND/DESCRIPTION

The potential use of adhesives in new construction in both in the shop and in the field is to be investigated. The possible benefits include reduced number of mechanical fasteners and prevention of crevice corrosion at the edges of the connection. Adhesives are widely used in other industries including aerospace, wind turbine blades, and light metal products. High strength bolts would be used in predrilled holes to clamp the pieces together after application of the adhesive. Epoxy adhesives with a shear strength of 3 ksi are available which can provide the friction shear strength of an A325 bolt. These hybrid bolt and adhesive joints could be readily used for shop connections and provide a slip capacity equal to a fully pretension bolt without the concern for proper bolt tensioning. Curing time of the adhesive and the effect of temperature upon the rate of curing rate are important parameters upon the ability of the adhesive to be used in the uncontrolled temperature of a fabricating shop or in the field.

OBJECTIVE

Evaluation of the use of structural adhesives in structural steel connections. The research should evaluate the shear strength of the adhesives, their creep behavior at expected steel temperatures in the bridge, curing of adhesives after joint assembly, and surface finish of the steel required to develop the shear performance. In addition, the long term performance of the adhesives under freeze-thaw conditions and exposure to deicing chemicals needs to be evaluated.

POTENTIAL BENEFITS

This initial project will provide the basis for the introduction of structural adhesives in bridge structures. Structural adhesives have been implemented in other industries due to their high strength and durability. A hybrid joint using bolts and adhesives will provide increased slip resistance, prevention of crevice corrosion at the edges of the connected material, and elimination of bolts added to the connection to satisfy maximum bolt spacing for corrosion protection.

RELATED RESEARCH

Current research in this area is predominantly related to lighter construction and structural composites. The proposed research will utilize the knowledge gained in other industries and evaluate the adhesives in our construction and exposure environment.

TASKS

1. Literature Survey and Selection of Candidate Adhesives for Evaluation
2. Short term shear tests to determine shear strength of adhesives with and without a tightened bolt.
3. Creep and exposure testing to determine the long term performance of the connection.
4. Design guides for prototype structural applications.

IMPLEMENTATION

The results of the study will provide the knowledge to begin the use of adhesives in steel bridge connections. It is expected that the initial use will be in shop connection of bracing and cross frame members. Further studies to develop design guides to predict the strength of large size bridge hybrid bolt-adhesive connections will be required.

ESTIMATE OF PROBLEM FUNDING

This research effort is anticipated to cost between $200,000 and $300,000.

RESEARCH PERIOD

This research is anticipated to last between 12 and 24 months.

RESEARCH PRIORITY

This research priority is high.

RELEVANCE

The bridge design community.

The aerospace, wind turbine, and automotive industries are active users of adhesives. The research performed and the products developed for these industries are a valuable source of information.

RNS DEVELOPER

Karl Frank, Consultant to NSBA

karl.frank@engr.utexas.edu

SPONSORING COMMITTEE

CO-SPONSORING COMMITTEE(S)

[Other committee(s) responsible for developing this statement.]

SOURCE INFORMATION

13 Appendix F - Presentations

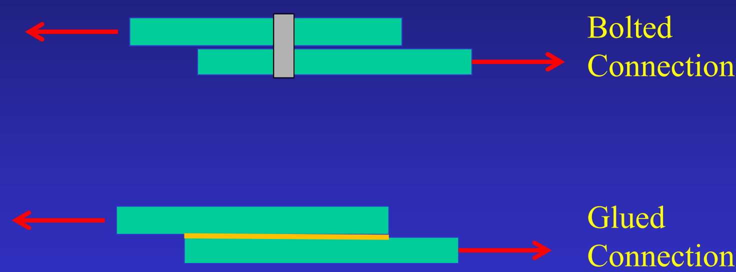
Application of Adhesive to Steel Bridge Construction

Karl H. Frank
Consultant
NSBA

Typical Field Connection

2

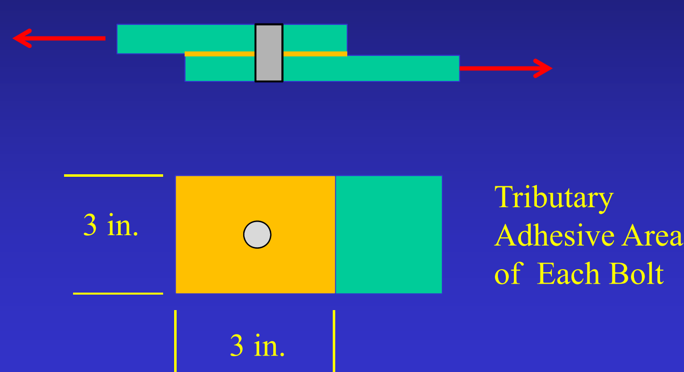
Adhesive Strength Versus High Strength Bolt



What Adhesive Strength Will Provide the Same Shear Strength as the bolt?

Assume bolts spacing is 3 inches in all directions.

Shear Strength Required



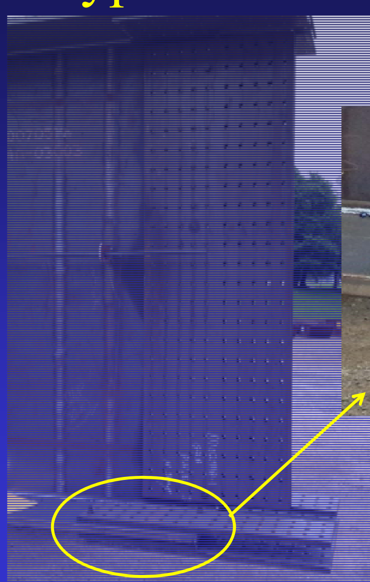
KHF

Equivalent Adhesive Shear Strength Based on 3 in. Bolt Spacing

	Shear Strength (kip)			Equivalent Adhesive Shear Strength psi		
A325 Bolt Dia. in.	A325F	A325N	A325X	A325F	A325N	A325X
0.875	19.5	21.6	27.7	2,350	2,600	3,340
1	25.5	28.7	36.2	3,150	3,540	4,470
1.125	28.0	31.7	40.1	3,550	4,020	5,090
A490 Bolt Dia. In.	A490F	A490N	A490X	A490F	A490N	A490X
0.875	24.5	27.4	34.6	2,990	3,340	4,220
1	32.0	35.8	45.2	4,000	4,480	5,650
1.125	40.0	45.3	57.3	5,150	5,830	7,380

KHF

Typical Field Splice with Fill Plate



Fill Plate to Match Thickness of Flange on the other side of the Splice

KHF

Gluing Fill Plates

- Reduce the number of bolts required-no fill plate reduction
- Can be applied in the shop and fill plate held in position by shipping bolts
- Research needed to set adhesive strength requirements and application requirements.

KHF

Bolted Field Splices

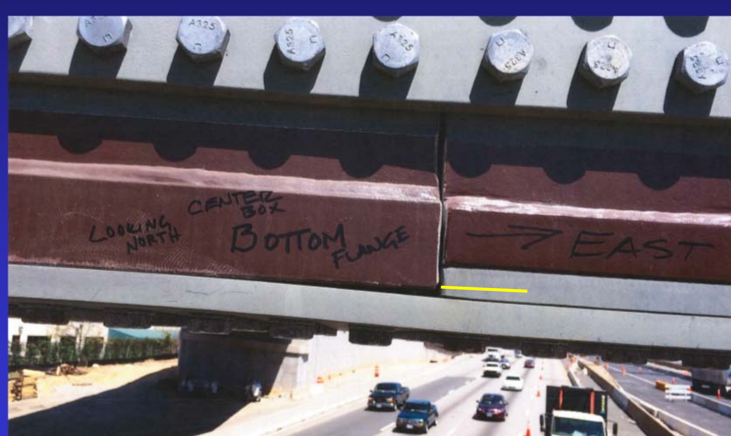
- Need a shop applied strip adhesive that will activate when bolts snugged.
  - Two part epoxy strips?
  - Anaerobic adhesive (applied in the shop?)
- Or an easy to apply adhesive in the field
  - Strips?
- Advantages:
  - Increased slip resistance
  - Sealing of joint

KHF

Sealing to Prevent Pack Rust

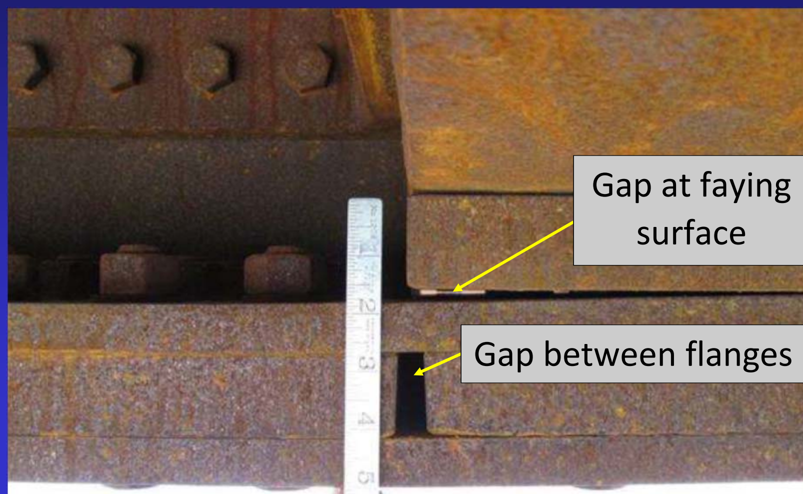
HDR

Sealing/Filling of Joints (Steel Grout)



KHF

Frame Through Pier Cap Joint



Grout

- Apply during field assembly of connection
  - Slow cure (days)
  - Minimal surface preparation
- After Joint assembly
  - Ability to seal end of connection between splice members
  - Injection into faying surface-must not reduce friction capacity
- Durable!!

KHF

Potential Steel Bridge Bolted Splice Market

Ronnie Medlock
High Steel Structures, LLC
Lancaster, PA

Steel Bridge Market

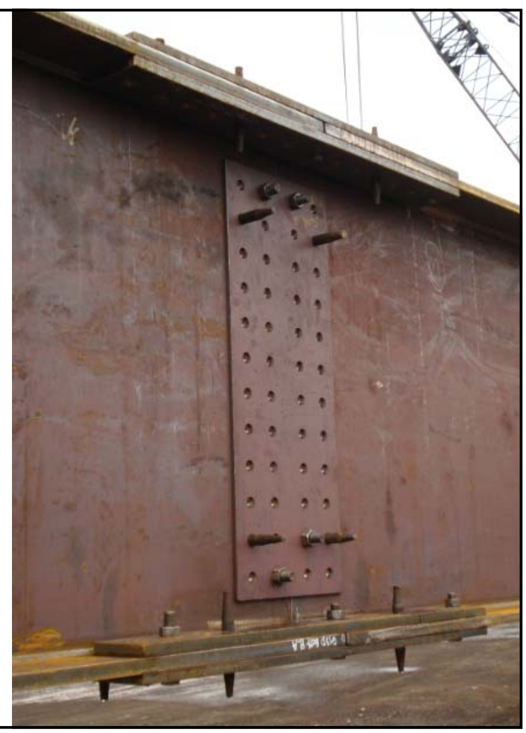
- I-girder Bridges – lion share of market
- Also
  - Tub-girder stringer bridges
  - Truss bridges
  - Cable-stay bridges
  - Arch bridges

I-girder Field Pieces

- Typically 120′ to 140′ long
  - Need reasonable lengths to ship and erect
  - Hence bridges have splices
  - Splices can be field welded, but this is not common; generally they are bolted

I-girder connections

- Consist of
  - Top flange to top flange
  - Bottom flange to bottom flange
  - Web to web
- Often include fill plates to facilitate thickness transitions



How large is the I-girder connection potential market?

- Use High Steel as a base
  - Perhaps 40% of the mid-Atlantic / New England market
  - Perhaps 10% of the national market
- Use COGO data

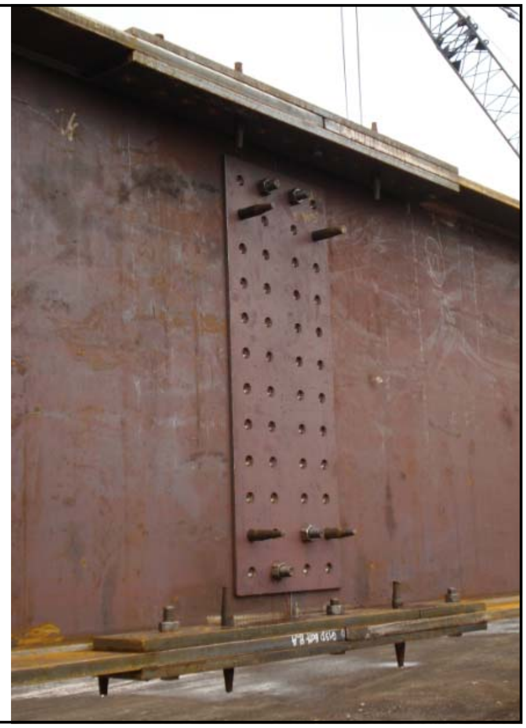
Use High Steel "COGO" jobs to collect data

- "COGO" is High Steel's in-house bridge geometry program
  - All bridges (High Steel and others) get "detailed" – i.e., shop drawing, CAD/CAM files, and bills of materials get produced
  - Fabricators use a blend of in-house and sublet detailing
    - Some sublet all of their detailing
    - High Steel sublets 35% of its detailing, but very few of its I-girder bridges
- High Steel's COGO has robust data on the project run in COGO
- Can assume all High Steel I-girder jobs are done in COGO (not so for other bridge types)

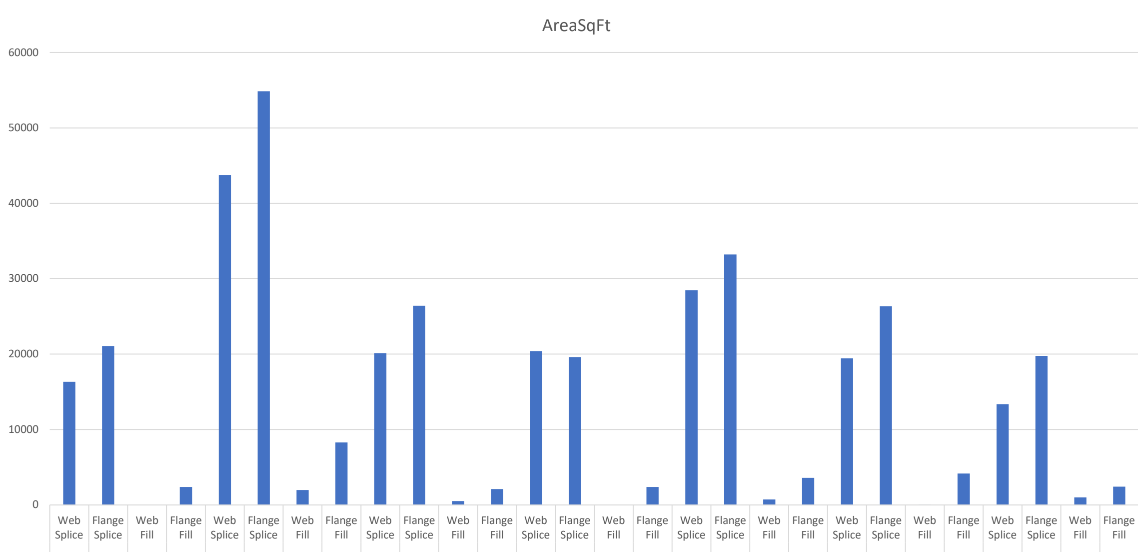
Web and Flange Connection Surface Area

- Assume that surface area is equal to the area of the splice plates and fill plates on job
- Assume that High Steel has 10% of the I girder market in its COGO system

Year	Category
2012	Web Splice
2012	Flange Splice
2012	Web Fill
2012	Flange Fill



I-girder Web and Flange Connection Area, SF



How large is the I-girder connection potential market?

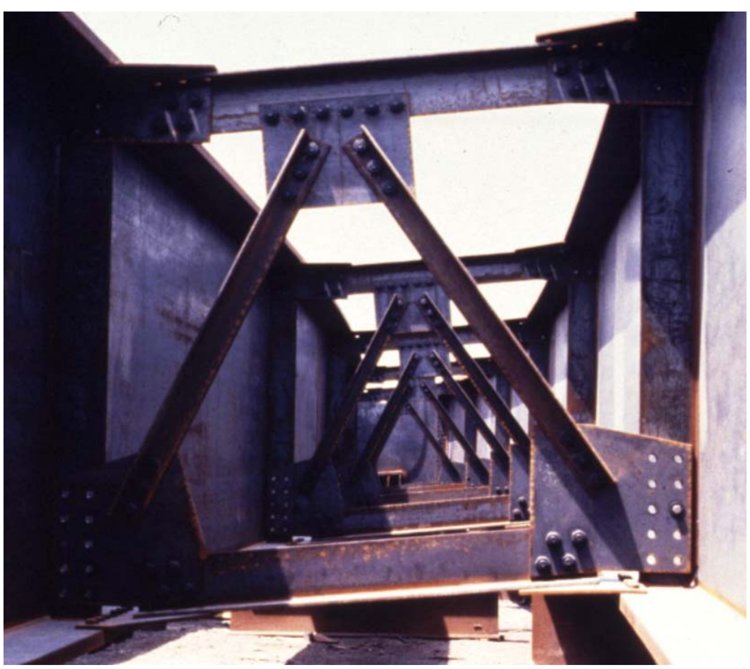
Total by year	
Year	SF
2012	39784
2013	108821
2014	49103
2015	42346
2016	65950
2017	49962
2018	36505

		SF
Average		56067
Average, w/o 2013		47275

If High Steel has 10% of the national market, then perhaps the annual square footage of main member connections is 50k x 10, or a half million SF per year

Not Considered – I girder Diaphragm and Lateral Brace Connections

- All I-girder bridges have diaphragms
  - Abutment and pier diaphragms
  - Intermediate cross frames
- Some I-girder bridges have lateral braces



Not Considered – I girder pier caps (boxes)

- Generally used to address clearance issues
- High Steel fabricates perhaps a dozen per year
- Owners are considering "all bolted" boxes - as non-fracture critical (FC) members known as internally redundant members (IRMs)


04/18/2007

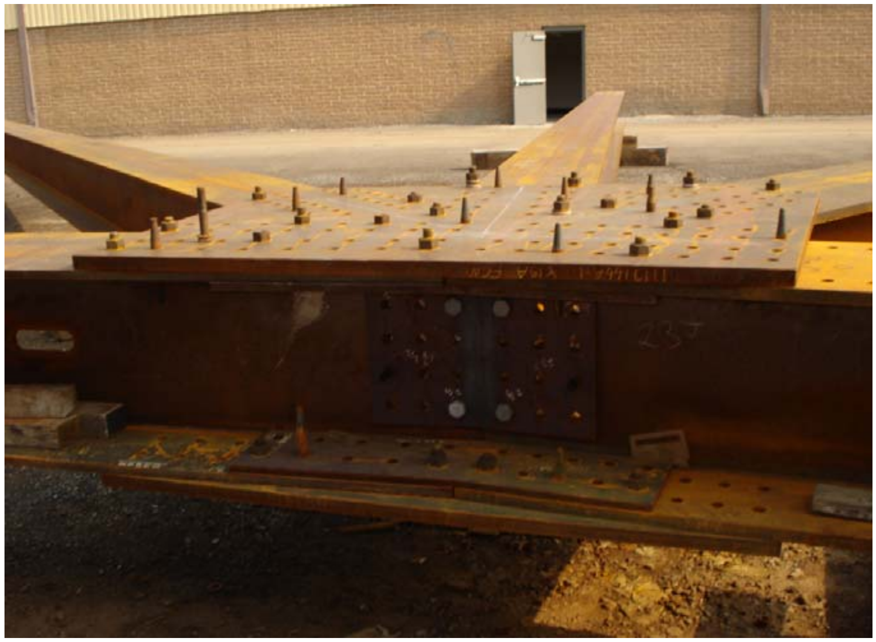
Tub girder bridges

- High Steel does a tub girder bridge about every other year
- Generally fairly long structures
- Includes
  - Web and flange splices
  - Internal diaphragms and lateral bracing

Trusses

- High Steel does about one truss per year
- Often railroad bridges
- Many fabricators do not do trusses (maybe High Steel does a third of the trusses)
- Multiple Connection Types

Trusses



Trusses

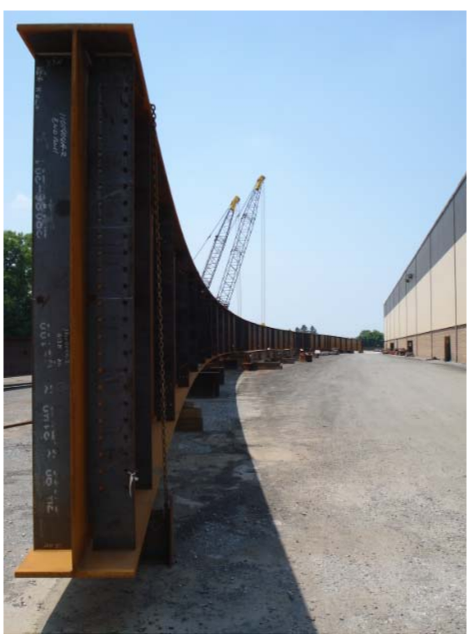
Cable Stay Bridges

- High Steel has done four
  - Ravenel 2003
  - Lewis and Clark 2015?
  - Kosciusko #1 - 2016
  - Kosciusko #2 – 2018
- Includes
  - Flange and web splices
    - Edge girder to edge grider
    - Edge girder to floor beam

Arch Bridges

- High Steel does one every three to five years
- Note the bolted tie (like bolted pier caps)

Others – Innerbelt Delta-leg Bridge



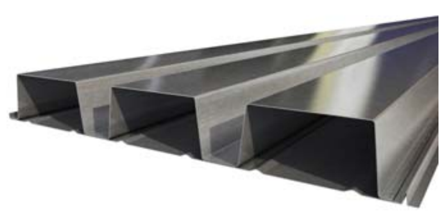
Possibilities?

Potential Applications of Adhesives in Steel Deck Construction

Thomas Sputo, Ph.D., P.E., S.E.
Technical Director
Steel Deck Institute

1

Steel Deck for Floor and Roof



2

Deck Fabrication

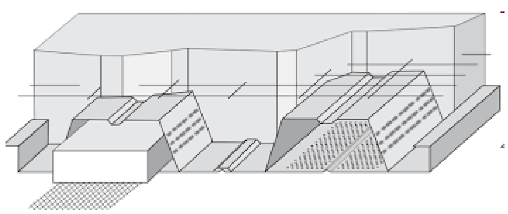
What is Cellular Deck?

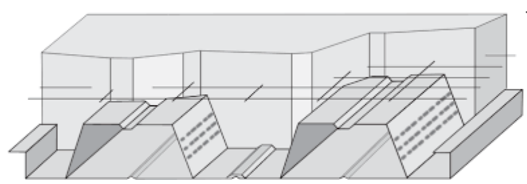
3

Roof Deck … Acoustical and Non-Acoustical

4

Floor Deck – Acoustical and Non-Acoustical





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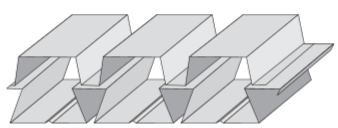
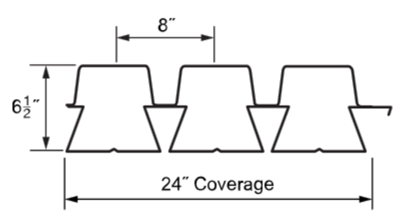
Cellular Deck Formed From 2 Sections (or more)

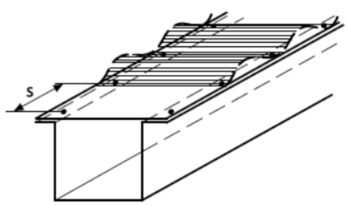




6

Cellular Deck Design Criteria

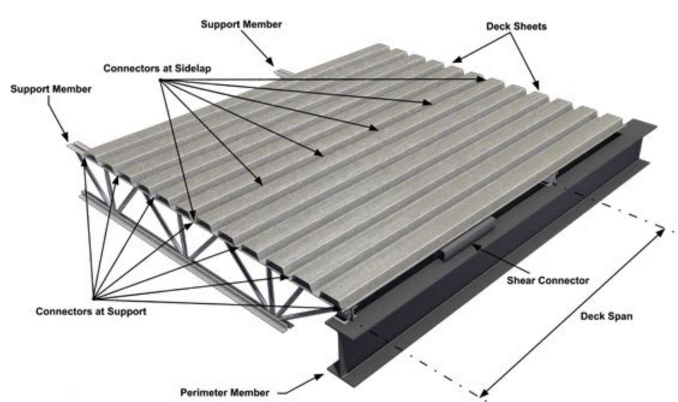
- AISI S100 Standard
  - Section strength based (basically Vq/I)
  - Plate element buckling based spacing limits



Current Connection Methods
- Resistance spot welds
- Rivets (less common)
- Clenching (even less common)
- Adhesives (rumors and myths)

7

Deck Installation

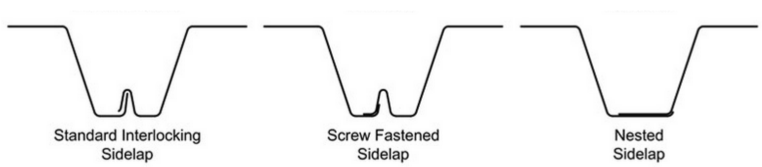


8

Deck Installation

Support Connections … Resist Tension and Shear
•Arc Spot Welds
•Screws
•Power Actuated Fasteners

Sidelap Connections … Resist Shear
•Screws
•Arc Seam Welds
•Crimping



9

Finishes Encountered

- Deck
  - Galvanized
  - Painted or Paint over Galvanized
  - Bare
- Support
  - Painted / Primed
  - Bare
  - Galvanized (rare)

10

Challenges / Questions

- Environment in shop and field
  - Temperature, moisture, etc.
- Speed / cost
- Effect on fire rated assemblies
- Ductility of adhesive joint
- Creep / Long term performance

11

FHWA Past and Future Research Opportunities

Justin Ocel, PhD, PE
Robert Spragg, PhD
Federal Highway Administration
Turner-Fairbank Highway Research Center

Not New

Klaiber, F. W., Dunker, K. F., Wipf, T. J., and Sanders, W. W., "Methods of Strengthening Existing Highway Bridges," NCHRP Report 293, Transportation Research Board, Washington DC., September 1987.

Table B-1. Summary of research related to epoxy bonding.

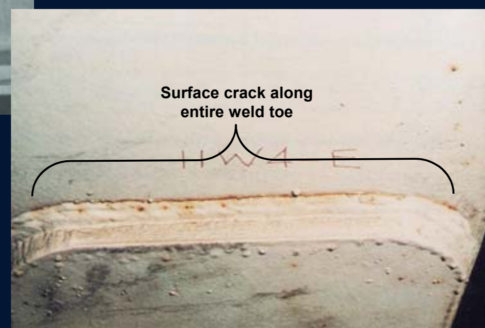
Author of Investigation	Year	Country	Reference No.	Pre-cracked Section	Reinforced & Unreinforced Sections	Under & Over Reinforced Sections	Effects of Shear Reinforcement	Dimensions of Concrete Beam	Compressive Strength of Concrete	Surface Preparation of Concrete & Steel	Surface Moisture of Concrete	Type of Adhesive	Glue Thickness	Bond Length	Mechanical Fasteners	Variations in Plate Geometry or Section	Multiple Layers of Plates	Plate Lapping	Cyclic Loading During Glue Hardening	Nature of Loading (Static, Dynamic)	Rate of Loading	Fatigue Tests	Creep	Exposure to Environmental Conditions	Temperature Effects	Humidity & Moisture Effects	Use in Actual Structure	Field Tests	Moment-Curvature Relationships	Steel to Steel	Steel to Concrete
Kajfasz	1967	Poland	150													X															X
L'Hermite, Bresson	1971	France	185													X						X	X					X			X
Bresson	1971	France	43									X					X											X			X
Ladner, Flueler	1574	Switzerland	172		X		X								X	X				X											X
Irwin	1975	United Kingdom	141																										X		X
Calder	1979	United Kingdom	53																					X	X	X					X
Teoh Han	1979	Malaysia	120	X																											X
Cusens, Smith	1980	United Kingdom	75				X					X	X					X		X		X			X	X				X	X
Jones, et al.	1980	United Kingdom	147									X	X				X	X													X
Raithby	1980	United Kingdom	255	X								X				X		X		X							X	X			X
Swamy, Jones	1980	United Kingdom	319																X												X
VanGemert	1980	Belgium	348											X						X							X				X
DeBuck, et al.	1981	Belgium	81						X		X	X		X			X			X					X						X
MacDonald	1981	United Kingdom	187																X											X	
Kostasy, et al.	1981	West Germany	271								X	X	X	X		X		X		X		X									X
Jones, Swamy	1982	United Kingdom	146			X										X															X
MacDonald	1982	United Kingdom	188	X								X	X	X		X	X	X													X
Mays, Tilly	1982	United Kingdom	202									X										X			X					X	
Cardon, Boulpaep	1983	Belgium	55																	X					X	X					X
Albrecht, et al.	1984	United States	2									X									X				X	X				X	
Jones, Swamy, Salman	1985	United Kingdom	145					X				X	X			X															X
Mecklenburg, ET. AL	1985	United States	205									X									X				X	X					X
VanGemert, VandenBosch	1985	Belgium	350																						X						X
Hoigard, Longinow	1986	United States	132																						X	X	X			X	
Wiener, Jirsa	1986	United States	368							X					X	X															X
Swamy, Jones, Bloxham	1987	United Kingdom	320	X									X			X	X														X

(X = hatched cell)

FHWA-RD-84-037

Albrecht, P., Sahli, A., Crute, D., and Evans, B., "Application of Adhesives to Steel Bridges," Report FHWA-RD-84-037, Federal Highway Administration, McLean, VA, November 1984.

Goal was to find fatigue life improvements to welded cover plates.



Adhesive Selection

Nara, H., and Gasparini, D., "Fatigue Resistance of Adhesively Bonded Structural Connections," Report No. 45K1-114, Department of Civil Engineering, Case institute of Technology, Ohio, September 1981.

39
- Manufactures submitted information

11
- Selected for preliminary testing

3
- Lord Versilok 204
- Dexter Hysol EA934
- Dexter Hysol EA9309

Adhesive Selection

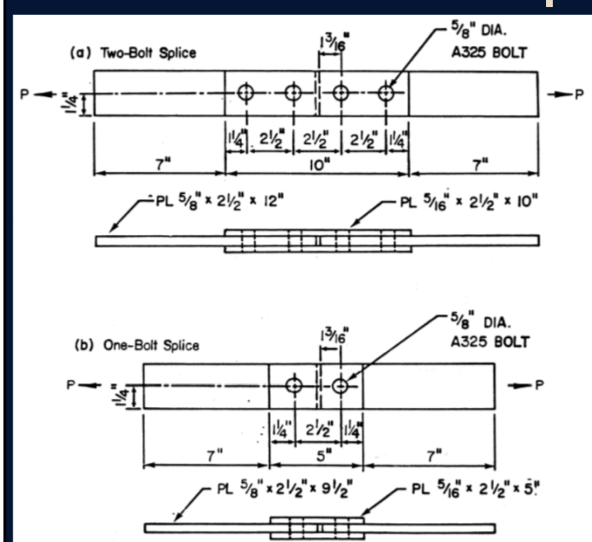
Preliminary pilot tests with 3” x $^{5}/_{16}$” 12” long attachments to tension flange of W14x30 steel beams

- Dexter Hysol EA9309
- Lord Versilok 201

A little less viscous than 204

Versilok 201 specimens had longer fatigue lives, it was used for the rest of the test program

Tension Test Specimens

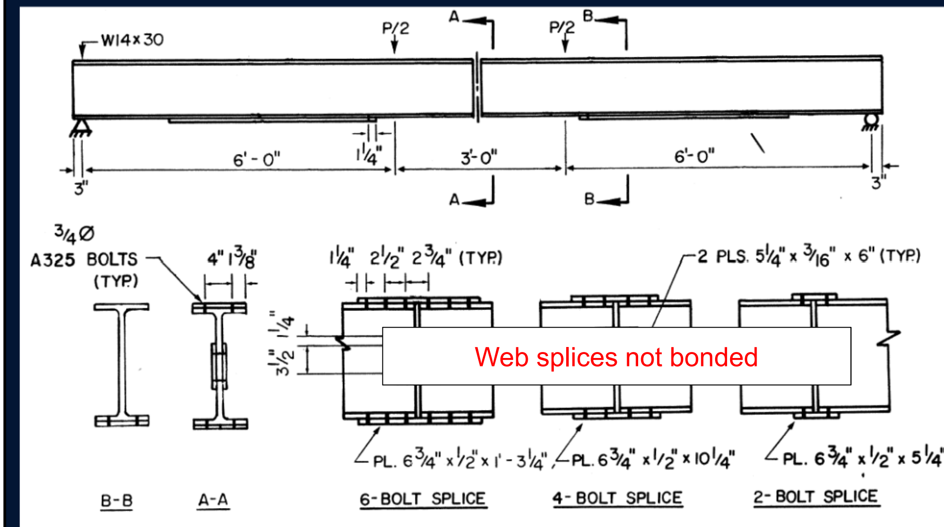


ASTM A588 steel

Bonded/ Unbonded

Fatigue/static

Beam Test Specimens



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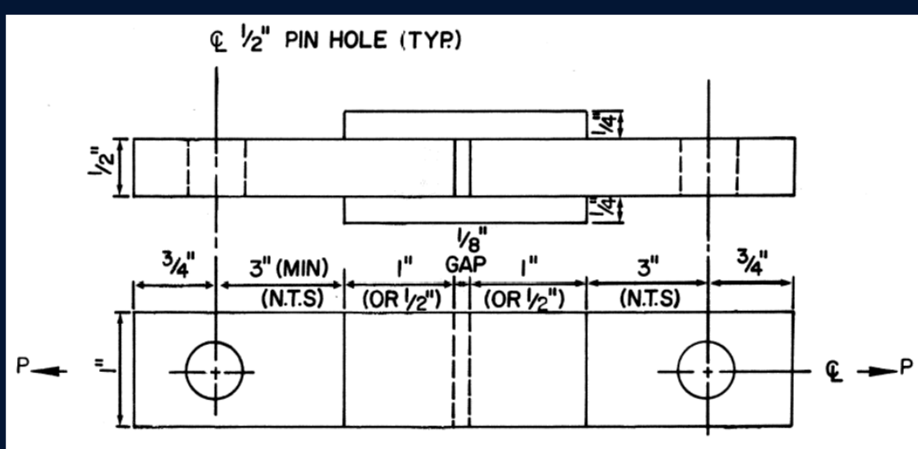
Creep Test Specimens



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Bond Line Thickness

- 10 mil thickness
  - used glass beads to ensure
- Bolts were tensioned before cure
  - squeezed epoxy away from bolt

Tension Test Static Results

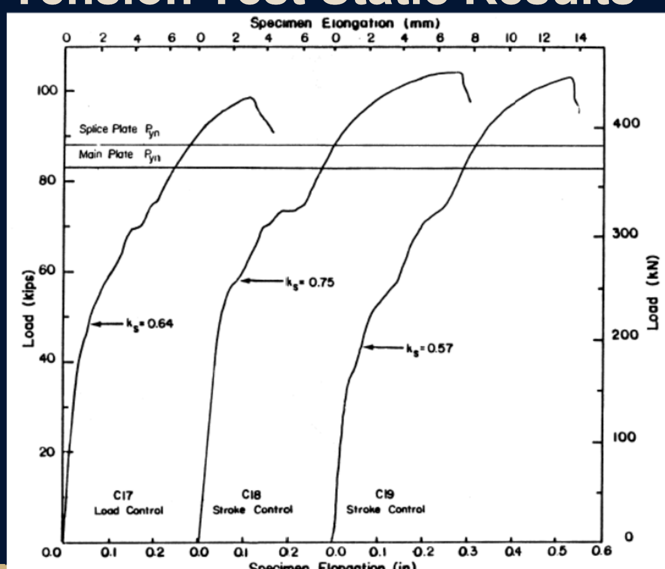


Figure 34: Load-elongation curves of nonbonded two-bolt splices C17-C19

Tension Test Static Results

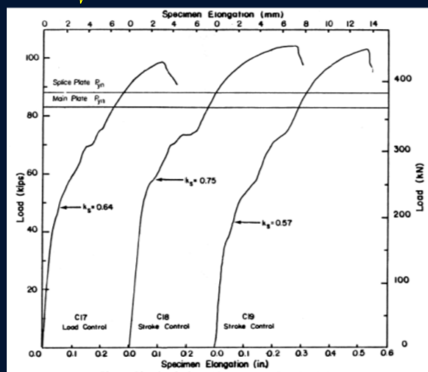


Figure 34: Load-elongation curves of nonbonded two-bolt splices C17-C19

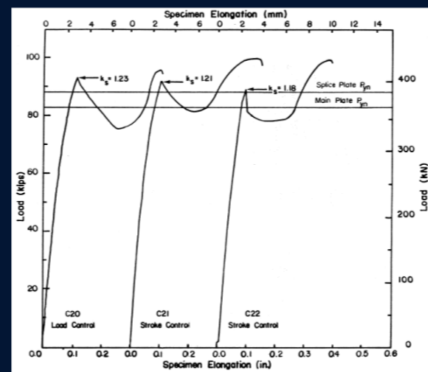


Figure 37: Load-elongation curves of bonded two-bolt splices C20-C22

unbonded

bonded

Tension Test Static Results

Table 22: Mean slip data for Series C tensile specimens and allowable shear stresses for friction-type joints

Specimen No.	Surface Condition	Mean Slip Coefficient $\bar{k}_s$	Standard Deviation s	Allowable Shear Stress of Bolts in Friction-Type Joints 5% (ksi)	1% (ksi)	FOS=1.45 (ksi)
Two-Bolt Splices						
C1-C4	Nonbonded[a]	0.352	0.051	16.9	14.7	15.3
C17-C19	Nonbonded	0.653	0.091	31.7	27.8	28.3
C5-C8	Bonded[a]	1.235	0.021	75.5	74.7	53.6
C20-C22	Bonded	1.207	0.025	73.4	72.3	52.4
All	bonded	1.23	0.023	74.5	73.6	53.1
One-Bolt Splices						
C9-C12	Nonbonded	0.585	0.071	29.5	26.4	25.4
C13-C16	Bonded	1.462	0.159	75.5	68.7	63.5
All Splices						
All[b]	Nonbonded	0.614	0.081	30.3	26.8	26.7
All	Bonded	1.31	0.150	66.9	60.4	56.9

Note: a. Splices with grinding marks on contact surfaces.
b. Specimens C1-C4 were excluded because of grinding marks on contact surfaces.

Tension Test Static Results

"In summary, the most important conclusion one can draw from the results of Chesson's exploratory tests and those described herein is that the adhesive fails before the gross area of the steel plate yields. Once the adhesive fails, the joints slips into bearing. Thereafter, the ultimate strength is limited by the tensile capacity of the member or the shear capacity of the bolts, whichever governs. It has not been possible to increase the ultimate strength of bonded and bolted joints to a value greater than strength of a joint that is bolted only. However, bonding greatly increased the slip load of bolted joints."

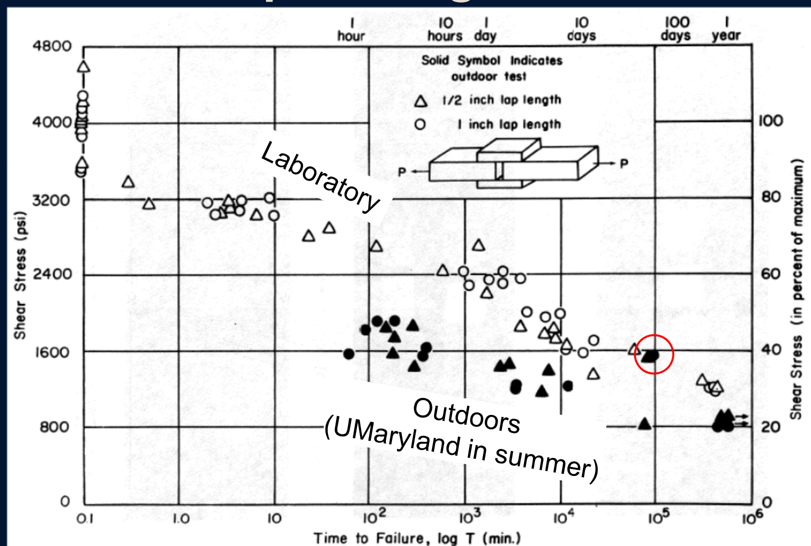
Tension Test Static Results

Takeaway for bolted connection design

1. ~~Bolted connection slip is checked at AASHTO Service II (1.00DL + 1.30LL)~~

2. Bolted connection failure is checked at AASHTO Strength I (1.25DL + 1.75LL)

Creep Testing Results



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FHWA-RD-86-037

Albrecht, P., Mecklenburg, M. F., and Evans, B., "Screening of Structural Adhesives for Application to Steel Bridges," Report FHWA-RD-86-037, Federal Highway Administration, McLean, VA, February 1985.

Tried to address the environmental factors from previous phase through material-level test.

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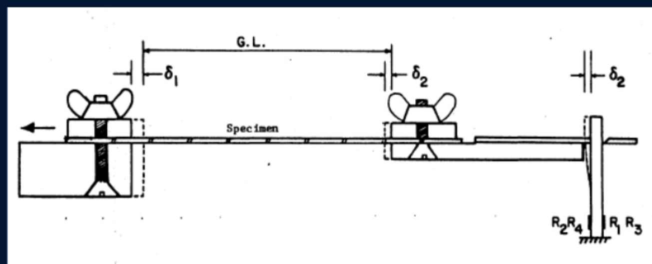
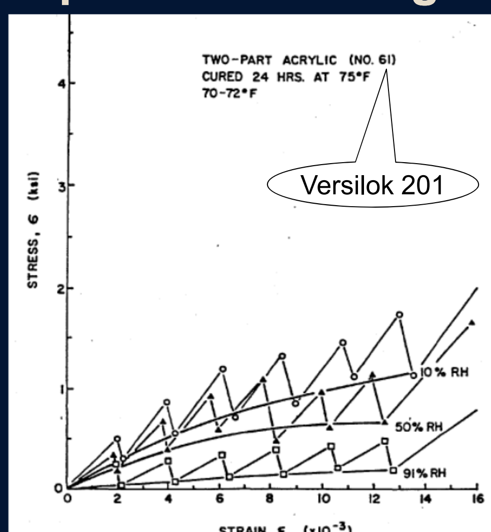
Test Method



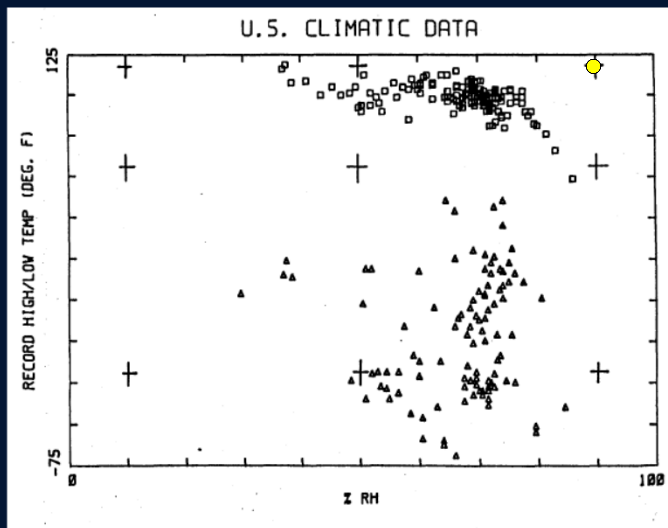
Tested bulk film coupon of just adhesive. Needed to be thin to equilibrate with the environment quickly.

0.2” x 8” x (9-11 mils)

Equilibrium Strength



Worst-Case Environment



120°F @ 90%RH picked as “worst-case”

Record Highs

Record Lows

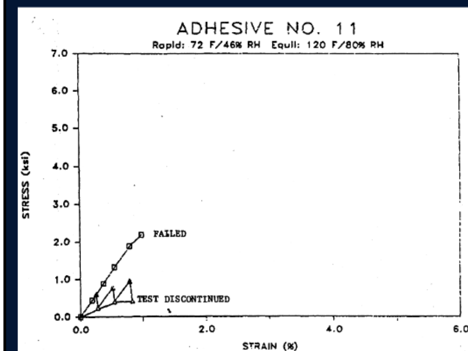
14

Results

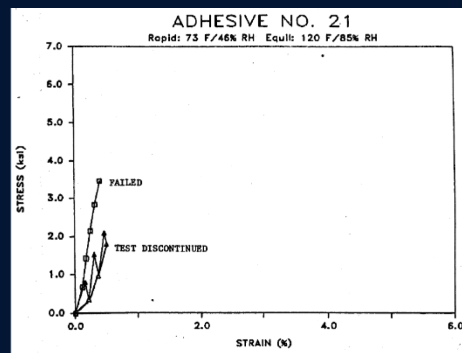
Tested 22 epoxies, 1 acrylic (blend of room temp cure and elevated cure)

- 2 — Developed equilibrium strength with first increment
- 6 — Relaxed to zero strength after first increment, some thereafter
- 9 — Relaxed to zero strength after first increment, none thereafter
- 5 — Developed no strength under equilibrium or rapid loading

Results



AF-111 (3M Company)
Epoxy film, 65 min. @ 250°F
(Bond shear strength = 4,000 psi)[a]



Eccobond 91-9 (Emerson Cuming)
Epoxy 2-part, 4 days @ 80°F
(Bond shear strength = 3,550 psi)[a]

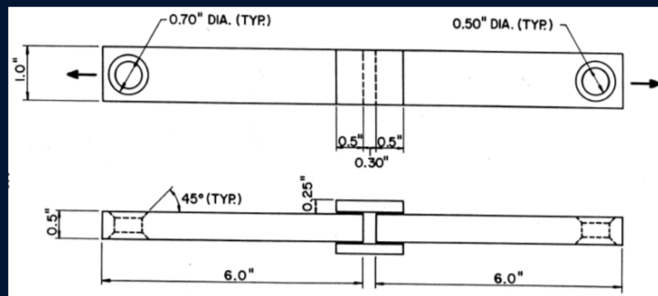
[a] From manufactures'' literature

FHWA-RD-87-029

Albrecht, P., Mecklenburg, M. F., Wang, J. R., and Hong, W. S., "Effect of Environment on Mechanical Properties of Adhesives," Report FHWA-RD-87-029, Federal Highway Administration, McLean, VA, February 1987.

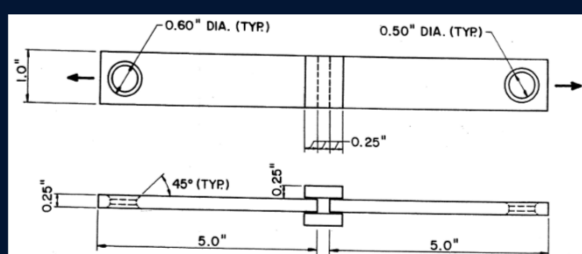
Continued testing of Eccobond 91-9, ~~3M AF-111~~, and American Cynamid FM-300

Rapid Load Shear Test Results



Environmental Soak (204-295 days)	Shear Strength, Eccobond 91-9 (ksi)	Shear Strength, FM-300 (ksi)
40°F @50%RH	3.98	5.13
80°F @50%RH	3.66	5.20
120°F @90%RH	2.32	3.50

Creep Shear Test Results



Test Environment	Shear Strength, Eccobond 91-9 (ksi)	Shear Strength, FM-300 (ksi)	Strength Ratio (Eccobond 91-9)	Strength Ratio (FM-300)
80°F @50%RH	2.50	2.80	0.68	0.54
120°F @90%RH	1.60	0.90	0.69	0.26

Punchline

"The creep strength under dead load, rather than the rapid-loading strength under maximum load, would control the design of joints…"

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Punchline

Takeaway for bolted connection design

1. ~~Bolted connection slip is checked at AASHTO Service II (1.00DL + 1.30LL)~~

2. Bolted connection failure is checked at AASHTO Strength I (1.25DL + 1.75LL)

Need to check adhesive portion for (0.26-0.69) times the short-term static shear strength)

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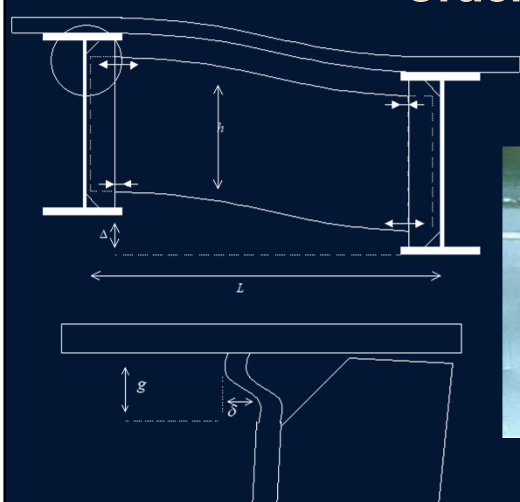
CFRP to Steel

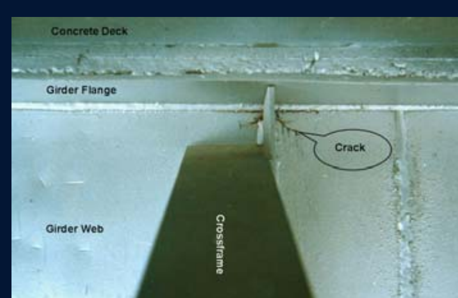
Shield, C., Hajjar, J. ,and Nozaka, K., "Repair of Fatigued Steel Bridge Girders with Carbon Fiber Strips," Report No. MN/RC-2004-02, Minnesota Department of Transportation, St. Paul, MN, December 2003.

- Sikadur 330 (Sika Corp.)
- Sikadur 30 (Sika Corp.)
- Polystrate EPOXY PLUS 25 (Devcon)
- DP-460NS (3M)
- Tyfo TC (Fyfe Co.)

Preferred due to ductility and ease of application

3M DP460NS to Retrofit Distortion Cracks



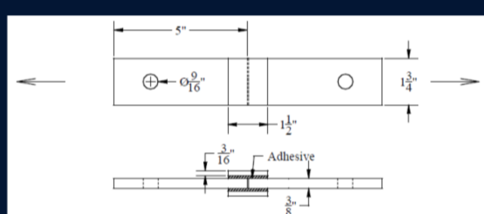


3M DP460NS to Retrofit Distortion Cracks

Hu, Y., Shield, C., and Dexter, R., "Use of Adhesives to Retrofit Out-of-Plane Distortion Induced Fatigue Cracks," Minnesota Department of Transportation, St. Paul, MN, February 2006.

Adhered double angle retrofit, 10 locations, intact after 3.5 years of field service.

3M DP460NS to Retrofit Distortion Cracks



Followed principles of ASTM D3528, but plate thicknesses increased for civil engineering applications

3M DP460NS to Retrofit Distortion Cracks

Exposed environment	Investigated parameters	Comparison	Changes in ultimate strength	Changes in stiffness
Air at 65°F	180 days	Compare E1-1 with B1	2%	-2%
	447 days	Compare E1-3 with B1	10%	15%
	180 days, cyclic loading	Compare E1-5 with B1	8%	8%
Immersion in tap water at 65°F	92 days	Compare E2-1 with B1	-7%	-5%
	201 days	Compare E2-2 with B1	-6%	-7%
Immersion in tap water at 111°F	92 days	Compare E3-1 with B1	-10%	-20%
	210 days	Compare E3-3 with B1	-13%	-20%
	210 days, cyclic loading	Compare E3-5 with B1	-59%	-59%
Air at -4°F	196 days	Compare E4-1 with B1	13%	-6%
	382 days	Compare E4-3 with B1	12%	7%
	197 days, cyclic loading	Compare E4-5 with B1	13%	-7%
Freeze and thaw chamber	92 days (552 cycles)	Compare E5-1 with B1	-3%	-14%
	193 days (1158 cycles)	Compare E5-2 with B1	1%	-9%
Temperature cycles, unloaded	197 days (14 cycles)	Compare E6-1 with B1	3%	-19%
	380 days (27 cycles)	Compare E6-3 with B1	7%	-14%
	207 days (15 cycles), cyclic loading	Compare E6-5 with B1	5%	-11%
Temperature cycles, loaded at 0.95 kips	211 days (15 cycles)	Compare E7-1 with B1	-19%	-32%
	370 days (26 cycles)	Compare E7-3 with B1	-30%	-36%
Outdoors	184 days	Compare E8-1 with B1	2%	-7%
	271 days, cyclic loading	Compare E8-3 with B1	3%	-9%
Fire broke out after outdoor exposure	371 days	Compare E9-1 with B1	-88%	-77%

Future FHWA Adhesive Research

1. AISC Innovations Workshop in May 2018
2. Asked my lab support contractor in Sep. 2018 to develop a white paper
3. Delivered by Dr. Karl Frank in Dec. 2018
   a) As a supplement to shear connections
   b) As the steel bridge eqivalent to “grout”
   c) Sealing of connections

Future FHWA Adhesive Research

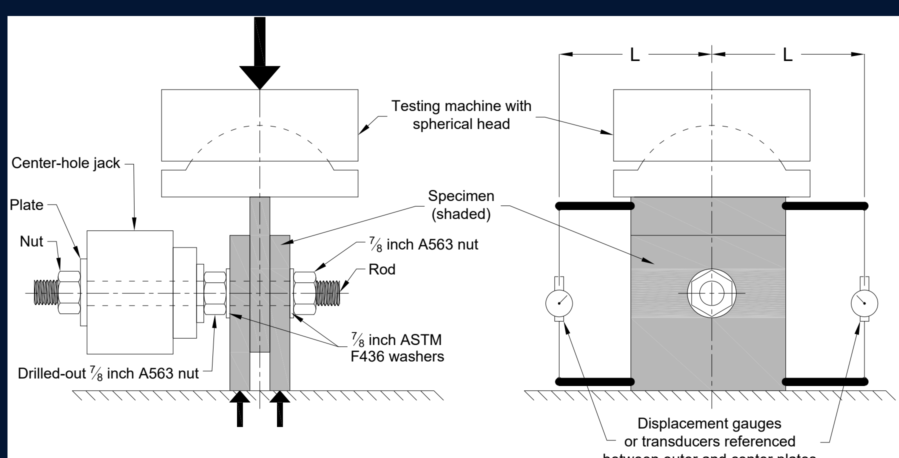
Can we reduce bolts?
- No worries for "sealing"
- Adhesive carries shear

Can we fill gaps?
- Steel equivalent to "grout"

- Toughened epoxies
  - What is shear strength?
  - Creep?
  - High temperature effects?

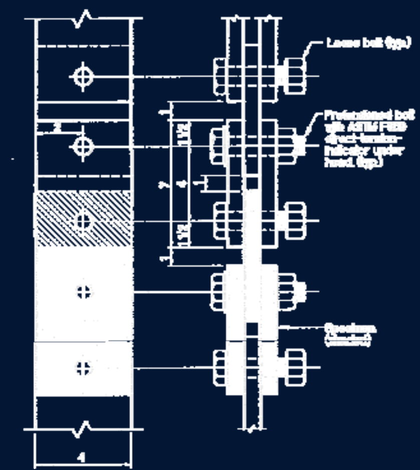
Initial Shear Testing

RCSC Short-Term Compression Test



Initial Shear Testing

RCSC 1000-hr Tension Creep Test



Initial Shear Testing Matrix

Variable	Ranges
Epoxy Type/Brand/Manufacturer	3M DP460NS Hysol EA9394 Devcon HP250
Humidity (conditioned 1 year)	50% RH 65% RH 85% RH
Temperature (at test time)	-30°F Room temperature 140°F
Thickness	5 mil 15 mil Snug tightened

* Shot blast to SSPC SP 6 *
** Tension bolts at testing? **

Initial "Steel Grout" Testing Matrix

1. Test each product using ASTM C579 specimen type. Though use 10-minute loading rate to better approximate long-term loading.
2. Short-term compression test larger diameter (6-12 inch) machined discs adhered together
   a. One disc smooth, one disc blasted.
   b. Adhesive thickness of ¼, ⅜ and ½ inch.
   c. Six replicates.
3. Repeat for long-term loading.

Initial "Steel Grout" Testing Matrix

Variable	Ranges
Epoxy Type/Brand/Manufacturer	Devcon Plastic Steel Putty (A) Stronghold MM1018 P Stronghold MM1018 FL WR Meadows EG-96 HP
Humidity (conditioned 1 year)	50% RH 65% RH 85% RH
Temperature (at test time)	Room temperature 140°F
Thickness	¼-inch ⅜-inch ½-inch


END

Lessons Learned from Testing Structural Adhesives

Structural Adhesives Workshop
American Institute of Steel Construction
August 13, 2019

Discussion

- Use of complimentary structural bonding to reduce mechanical, structural fasteners/ bolts
- Factors:
  - Adhesive strength
  - Fasteners as primary or redundant attachment?
  - Service environment
  - Life expectancy and maintenance
  - Application feasibility/ process

Recent experience

- Rampart LLC evaluated several commercial structural adhesives in 2016-2017 for metal to non-metallic bonding
  - 2-part epoxies (and a few moisture cured urethanes) for seawater immersion service
  - Mostly evaluated over painted steel; some direct to metal evaluation; some to thermal spray coatings
  - Evaluated via pull-off adhesion, 90-degree peel, T-peel, lap shear, slow strain rate ("creep") and cathodic disbondment testing
- Results down-selected, two commercial products currently being used for most multi-layer systems with adherends
- Consistent results when adhered and tested consistently; variations in sample prep and test protocols can vary results
- "Weakest link" in multilayer systems
- Fasteners used in some applications, but primarily as "redundant" in design

Analysis Lessons Learned/ Factors to Consider/ Importance Of

- Interface Preparation:
  - Cleanliness, painting, sanding of paint surface, adhesion promoters/ pretreatments
- Bond line thickness:
  - Use of beads/ spacers; importance of product viscosity; application method/ tools; ability to vacuum
- Cure:
  - Cure time, ability to wet out, fast cure vs. amount of open time, heat vs. ambient cure
- Metal-to-metal considerations:
  - Gap tolerances; slip resistance; structural property analysis
- Adhesives composition:
  - Epoxy polymer-based resins; use of glass, carbon, or polyamide reinforcing fibers
- Lab Testing:
  - Tensile, lap shear, wedge, peel testing (pros/ cons)
- Additional issues to consider:
  - Repair; inspection (initial and field); impact during service

Draft Requirements

- Use of adhesive for complimentary structural bonding
- Intended use in atmospheric exposure (microenvironments related to connection points)
- Long-term durability
- High shear, tensile, and peel strengths
- Ability to bond metal to metal (steel to steel) or paint to paint surfaces
- Ambient cure; post cure not required
- Service range capability of -20 degrees F to 150 degrees F

ADHESIVES IN STEEL BRIDGE FATIGUE APPLICATIONS

AISC Structural Adhesives Workshop
August 13, 2019, Chicago, IL

Caroline Bennett, Ph.D., P.E.
John E. & Winifred E. Sharp Professor
CEAE Department , University of Kansas

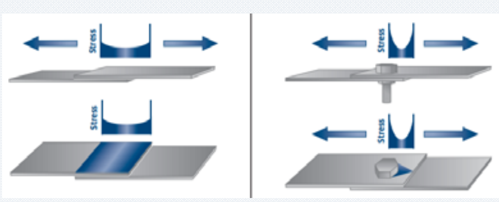
Hayder Al-Salih, Graduate Research Assistant
CEAE Department , University of Kansas

KU THE UNIVERSITY OF KANSAS
School of Engineering

GENERAL ADVANTAGES OF ADHESIVES

Structural Adhesives vs. Mechanical Fasteners

- More even stress distributions
- Aesthetics
- Minimizes/eliminates secondary operations like punching holes
- Reduction in weight
- Forms a seal which can protect the joint from corrosion
- Ability to join geometrically complex surfaces



Source: Henkel website materials

Structural Adhesives vs. Welding

- Allows joining of dissimilar substrates with dissimilar melting points
- No distortion or warpage, discoloration, embrittlement of the heat affected zone, or residual stresses
- Significantly less skill required than welding
- Eliminates weld discontinuities such as undercut, overlap, and cracks that can severely decrease fatigue life.
- Can easily join irregularly shaped surfaces
- Can bond heat-sensitive materials

GENERAL CHALLENGES TO USING ADHESIVES IN STRUCTURAL STEEL APPLICATIONS

- Need to overlap material which requires more material compared to butt joints.
- Visual inspection is limited
- Surface preparation for the use of adhesives can be difficult in the field.
- Some adhesives require long curing times which can delay production and assembly
- Joints cannot be disassembled easily
- Cannot provide the same unit strength as welds
- There remains uncertainty regarding the environmental durability of adhesives.
  - Service conditions (temperature, humidity, indoor/outdoor use, exposure to ultraviolet rays)
  - Stress type and magnitude (shear, tensile, compression, cleavage, peel etc.)
  - Contact to chemicals that can affect the structural integrity of the bond (i.e. oil, gasoline, acids, etc.)
  - Exposure to mechanical demands (abrasion, impact, vibration, fatigue loading.)
  - Exposure to to thermal cycles
- Challenges in maintaining bond during fatigue loading

FATIGUE PERFORMANCE OF ADHESIVES – KU RESEARCH

Bending Fatigue

- Hysol resin (Loctite Hysol 9412)

Tensile Fatigue

- Hysol resin (Loctite Hysol 9412)

Distortion-Induced Fatigue

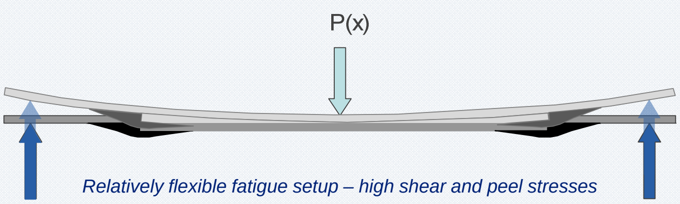
- West System (105 Epoxy Resin / 206 Slow Hardener)
- Hysol resin (Loctite Hysol 9412)
- Epibond 420 A/B (Huntsman product)

- Performance under different fatigue loading conditions
- Performance of various adhesives
- Bond tenacity
- Influence of bond thickness
- Influence of fabrication techniques
- Use of secondary elements (bolts, etc.)

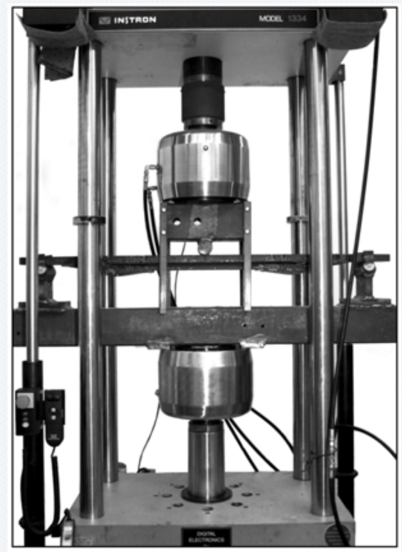
BENDING FATIGUE – ADHESIVELY-BONDED OVERLAYS

Welded cover plate detail

CFRP overlay element



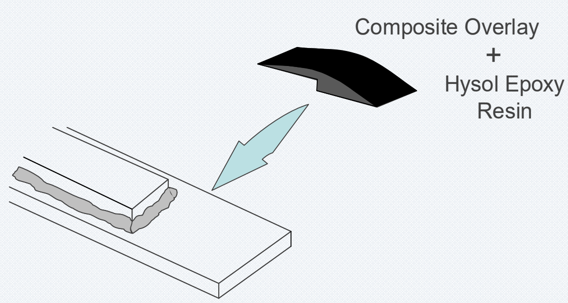
Relatively flexible fatigue setup – high shear and peel stresses



BENDING FATIGUE – ADHESIVELY-BONDED OVERLAYS

Bonding Procedure

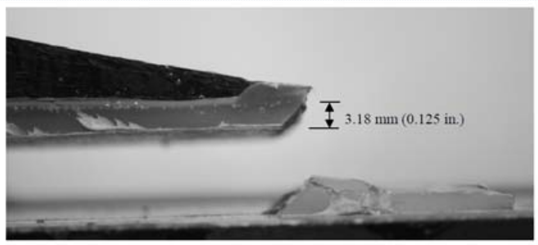
- Hysol (Loctite 9412)
  - Measured E = 303 ksi;
    Nominal shear strength = 4 ksi
- Steel was prepped with a hand grinder and degreased with mild acid & isopropyl alcohol.
- The CFRP doubler was roughened with 100-grit sandpaper and cleaned with isopropyl.
- Mastic material was used to dam around the bond area.
- Steel ball bearings were used as spacers to achieve the desired bond thickness.
- Polyester fabric was used as a resin captivation layer within the bond.
- The surface of the doubler was coated with a thin layer of Hysol to decrease the potential for voids
- Bond was cured at room temp for 48 hrs before loading, while clamped



BENDING FATIGUE – ADHESIVELY-BONDED OVERLAYS

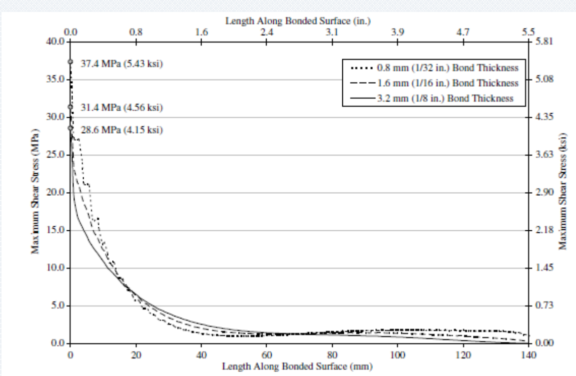
Effects of Bond Characteristics on Frequency of Debonding

- We did not find a strong correlation between bond thickness and debond frequency during experimental tests, although FEA predicted that thicker bonds would experience lower peel & shear stresses.
- Resin captivation layer (polyester "breather cloth") dramatically improved fatigue life
  - For thick bonds, several layers of the fabric were used. A small hole was cut in the fabric to accommodate each ball bearing. The fabric dimensions were at least as large as the area being bonded.
- Resin pool at ends of CFRP overlay elements – lower debonding frequency than cases where the bond was trimmed back to the edge of the overlay (reduced stress concentration at point of high shear demand)

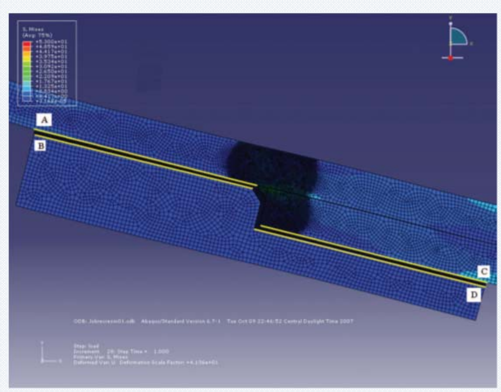


BENDING FATIGUE – ADHESIVELY-BONDED OVERLAYS

Shear stresses along Path A, for varied bond thickness



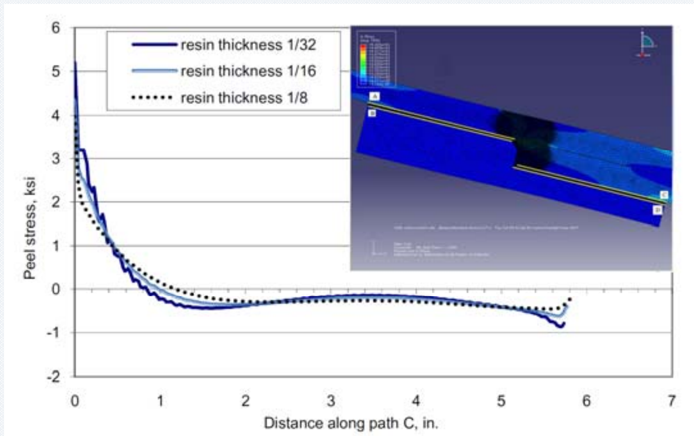
Stress extraction paths



Kaan, B., Alemdar, F., Bennett, C., Matamoros, A., Barrett-Gonzalez, R., & Rolfe, S. (2012). "Fatigue Enhancement of Welded Details in Steel Bridges Using CFRP Overlay Elements," Journal of Composites for Construction, ASCE,16(2) 138-149.

BENDING FATIGUE – ADHESIVELY-BONDED OVERLAYS

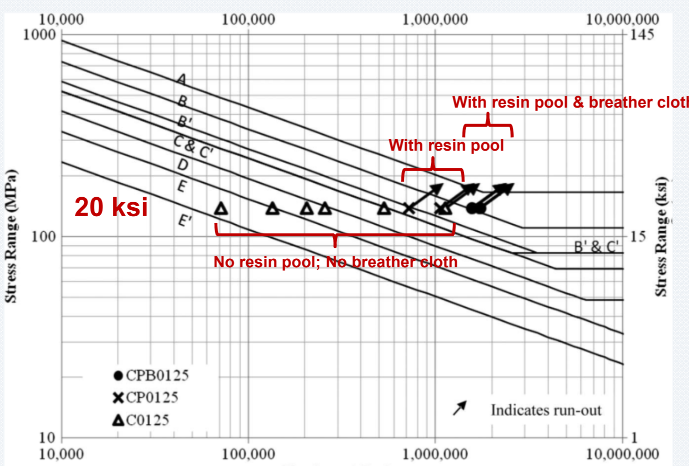
Peel stresses along Path C, for varied bond thickness



Alemdar, F. (2010). "Use of Composite Materials to Repair Steel Structures Vulnerable to Fatigue Damage." M.S. Thesis, Department of Civil, Environmental, and Architectural Engineering, University of Kansas, Lawrence, KS.

BENDING FATIGUE – ADHESIVELY-BONDED OVERLAYS

Fatigue results bond life, for specimens with 1/8" thick bond layers

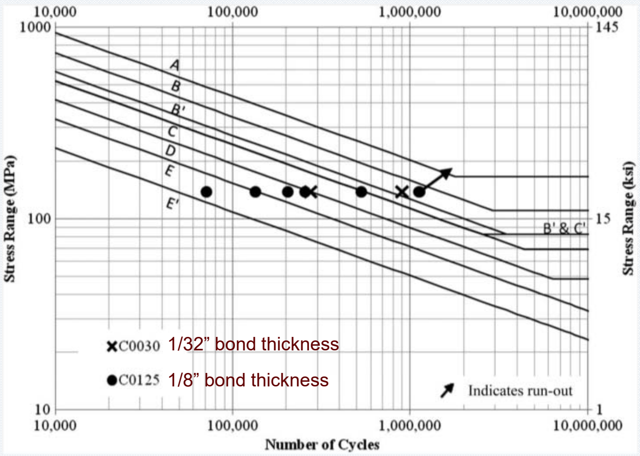


Kaan, B., Alemdar, F., Bennett, C., Matamoros, A., Barrett-Gonzalez, R., & Rolfe, S. (2012). "Fatigue Enhancement of Welded Details in Steel Bridges Using CFRP Overlay Elements," Journal of Composites for Construction, ASCE,16(2) 138-149.

Alemdar, F., Matamoros, A., Bennett, C., Barrett-Gonzalez, R., & Rolfe, S. (2012). "Use of CFRP Overlays to Strengthen Welded Connections under Fatigue Loading," Journal of Bridge Engineering, ASCE, 17(3), 420-431.

BENDING FATIGUE – ADHESIVELY-BONDED OVERLAYS

Fatigue results for bond life, for specimens with 1/32" and 1/8" thick bond layers

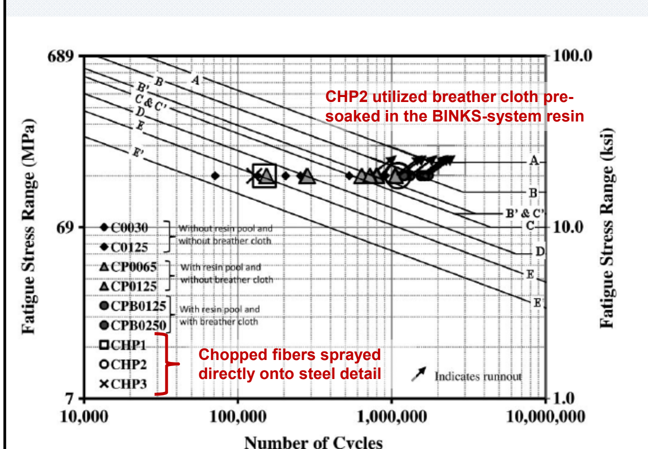


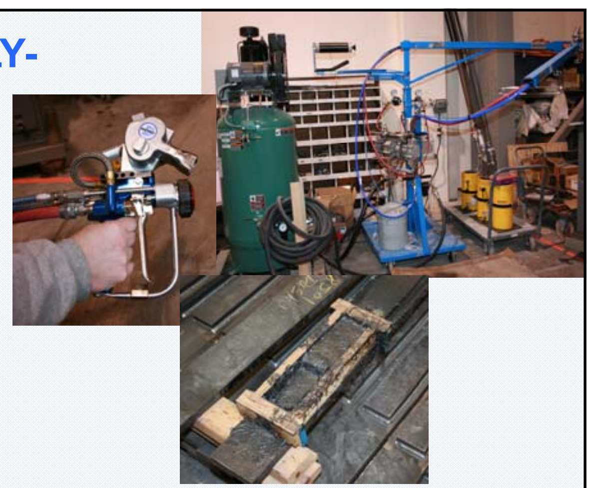
- Not a large difference in behavior between specimens with 1/32" and 1/8" bond thicknesses.
- Fabrication considerations (breather cloth, resin pool) appeared to outweigh bond thickness in terms of fatigue performance.

Kaan, B., Alemdar, F., Bennett, C., Matamoros, A., Barrett-Gonzalez, R., & Rolfe, S. (2012). "Fatigue Enhancement of Welded Details in Steel Bridges Using CFRP Overlay Elements," Journal of Composites for Construction, ASCE,16(2) 138-149.
Alemdar, F., Matamoros, A., Bennett, C., Barrett-Gonzalez, R., & Rolfe, S. (2012). "Use of CFRP Overlays to Strengthen Welded Connections under Fatigue Loading," Journal of Bridge Engineering, ASCE, 17(3), 420-431.

BENDING FATIGUE – ADHESIVELY-BONDED OVERLAYS

Fatigue results for bond life





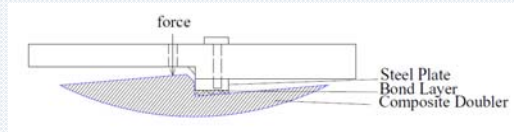
- Spray machine, non-atomized resin LEL chopper system commercialized by BINKS
- Vinyl ester resin with Norox MEKP-925 catalyst and graphite fiber yarn
- Sprayed in layers approximately 1/8" thick and compacted

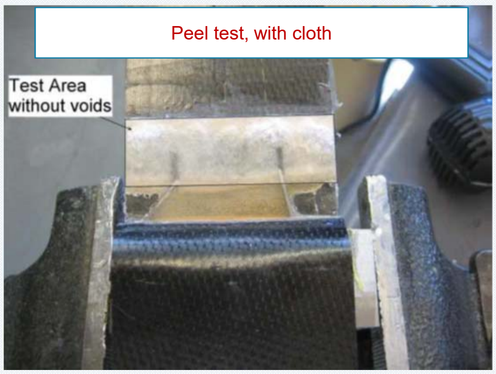
Alemdar, F., Matamoros, A., Bennett, C., Barrett-Gonzalez, R., & Rolfe, S. (2012). "Use of CFRP Overlays to Strengthen Welded Connections under Fatigue Loading," Journal of Bridge Engineering, ASCE, 17(3), 420-431.

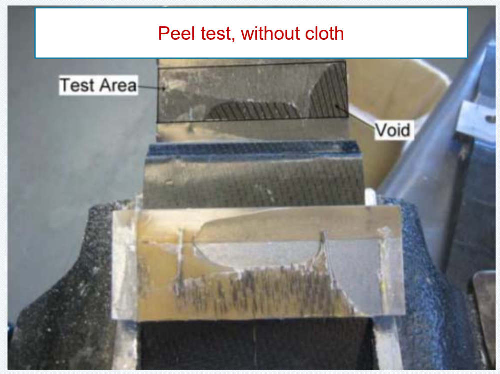
MONOTONIC PEEL TESTS

Resin Captivation Layer

- Elimination of voids; allowed air bubbles in the resin to escape
- Prevented propagation of fatigue cracks through the interface resin layer





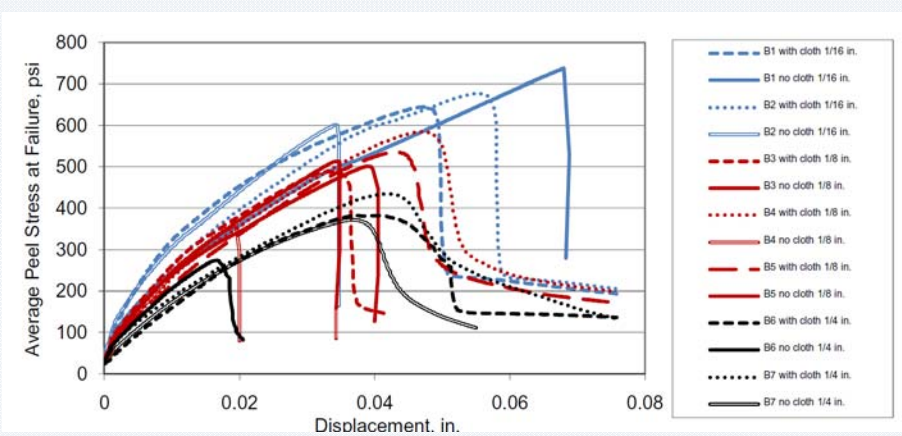


Alemdar, F., Matamoros, A., Bennett, C., Barrett-Gonzalez, R., and Rolfe, S. (2011). "Improved Method for Bonding CFRP Overlays to Steel for Fatigue Repair," Proc. of the ASCE) / SEI Structures Congress, Las Vegas, NV, April 14-16, 2011.

MONOTONIC PEEL TESTS

Resin Captivation Layer

- Monotonic peel tests of epoxy resin layer with steel plates
- Bond thicknesses of 1/16", 1/8", and 1/4" were tested



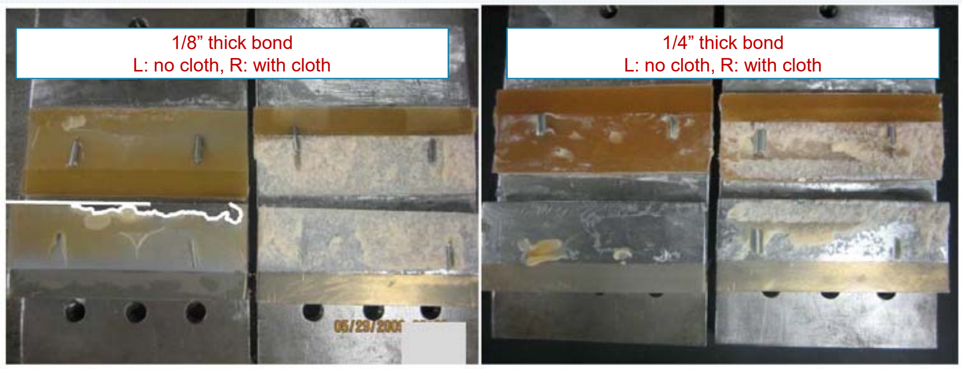
- In general, bonds with breather cloth achieved higher deformations at failure
- Specimens with breather cloth retained a residual capacity ~30% of the maximum stress

Alemdar, F., Matamoros, A., Bennett, C., Barrett-Gonzalez, R., and Rolfe, S. (2011). "Improved Method for Bonding CFRP Overlays to Steel for Fatigue Repair," Proc. of the ASCE) / SEI Structures Congress, Las Vegas, NV, April 14-16, 2011.

MONOTONIC PEEL TESTS

Resin Captivation Layer

- Voids developed in pure resin bond; lack of voids in the bond with breather cloth
- For resin layers with breather cloth and for thin bonds, failure tended to occur through the middle of the resin layer, with residues remaining attached to both steel plates. This indicates that tensile strength of the resin was the limiting factor, not the bond between the steel and resin.



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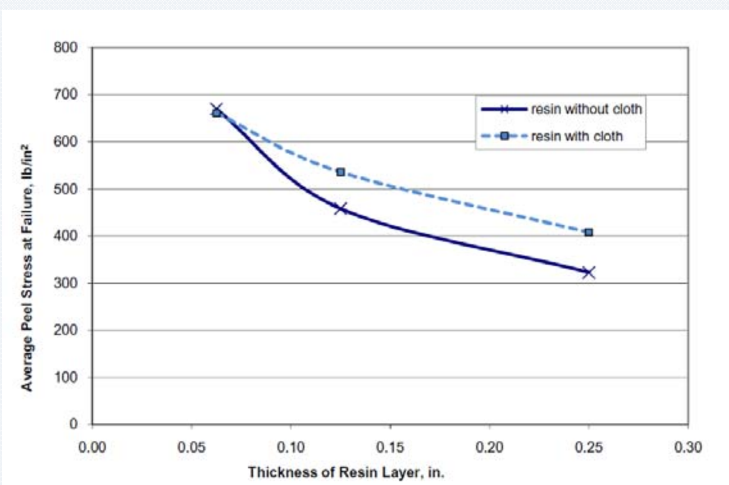
MONOTONIC PEEL TESTS

Resin Captivation Layer



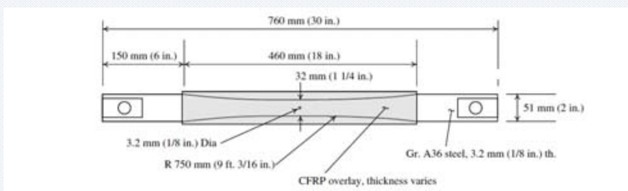
- Peel strength of the bond decreased with increasing thickness
- Reduction in strength with thickness was less pronounced for specimens with breather cloth
- For very thin bonds, presence of the breather cloth had a negligible effect on strength, while the difference was on the order of ~25% for thick resin layers.

Alemdar, F., Matamoros, A., Bennett, C., Barrett-Gonzalez, R., and Rolfe, S. (2011). "Improved Method for Bonding CFRP Overlays to Steel for Fatigue Repair," Proc. of the ASCE) / SEI Structures Congress, Las Vegas, NV, April 14-16, 2011.

TENSILE FATIGUE – ADHESIVELY-BONDED OVERLAYS

CFRP Doublers Adhered to Steel Plate Specimens

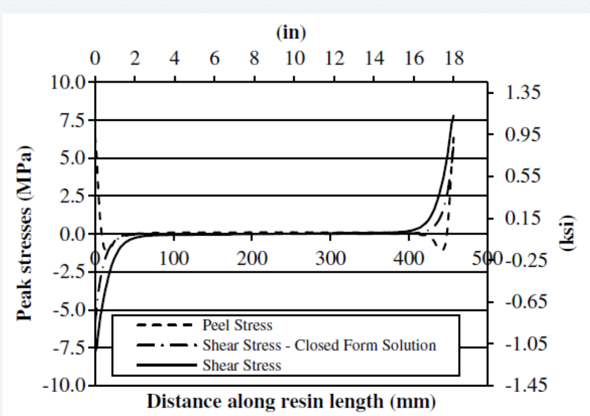
- Steel plate thickness – 1/8” and 1/4”; CFRP doubler thicknesses – 1/16” – 1/2”
- t_{resin} = 24 mil, Hysol resin
- 48 hr, room temp cure while clamped
- Cycled at stress ranges of 24-38 ksi (based on steel net section)
- Of the 15 specimens tested with initial crack lengths of 0.3”, only one experienced debonding before reaching run-out – thickest steel plate (1/4”) with the thickest CFRP doubler (1/2”)



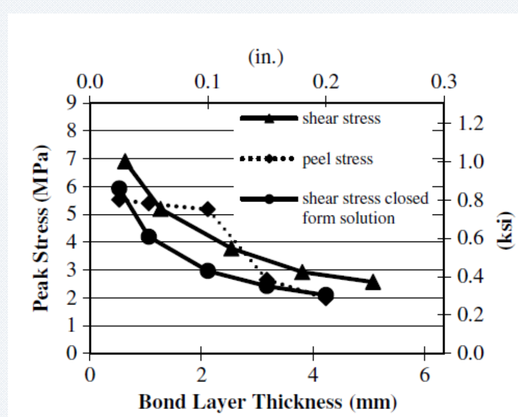
Alemdar, F., Gangel, R., Matamoros, A., Bennett, C., Barrett-Gonzalez, R., Rolfe, S., and Liu, H. (2014). “Use of CFRP Overlays to Repair Fatigue Damage in Steel Plates under Tension Loading,” Journal of Composites for Construction, ASCE, 18 (4).

TENSILE FATIGUE – ADHESIVELY-BONDED OVERLAYS

Computed Stress Demand along Resin Layer (for t_{resin}=20 mil)



Computed Variation of Peak Shear and Peel Stresses as a Function of Bond Thickness



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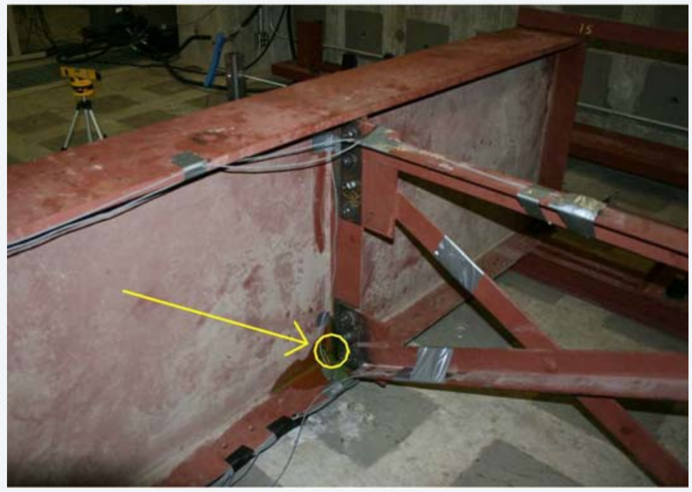
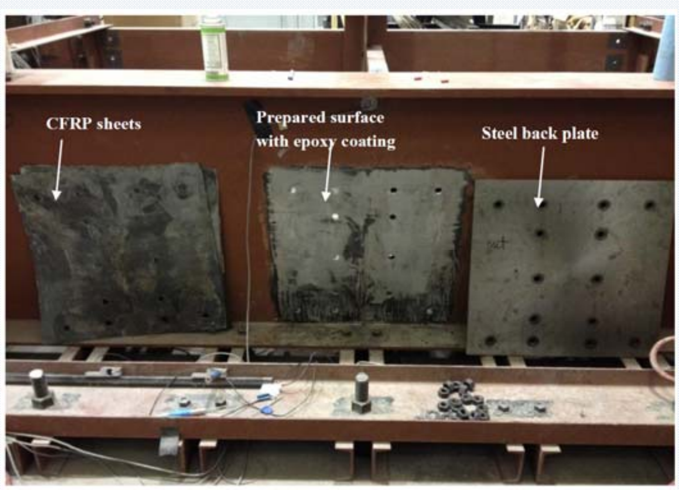
DISTORTION-INDUCED FATIGUE – ADHESIVELY-BONDED OVERLAYS



DISTORTION-INDUCED FATIGUE – ADHESIVELY-BONDED OVERLAYS



DISTORTION-INDUCED FATIGUE – ADHESIVELY-BONDED OVERLAYS

CFRP-Steel Sandwich Repair:

1. Laminar CFRP materials were cut to size
2. Holes were drilled in the graphite sheets using a metal hole punch
3. Steel surfaces were prepped with grinding and isopropyl alcohol
4. Laminates were bonded to the steel with two-part WEST resin (West System 105 Epoxy Resin + West System 206 Slow Hardener) brushed on; layers were applied one at a time
5. Steel elements were attached over the fibers and bolts tensioned.
6. 48-hr room temp cure

Testing was conducted til run-out for two trials; no crack propagation or debonding were observed with the retrofit in place.

DISTORTION-INDUCED FATIGUE – ADHESIVELY-BONDED OVERLAYS

Composite Block (Glass):

- West System two-part epoxy (West System 105 Epoxy Resin + West System 206 Slow Hardener)
- Conventional mat fiberglass
- ¾" dia threaded rods, snug tight
- Some debonding was noted during fatigue test trial at a high load level; still significantly slowed crack propagation

Bun, S., Bonet, E., Matamoros, A., Bennett, C., Rolfe, S., Barrett-Gonzalez, R. (2014). "Repair of Distortion-Induced Fatigue Damage in Steel Bridges using Composite Materials." Proc. European Bridge Conference, London, U.K.

DISTORTION-INDUCED FATIGUE – ADHESIVELY-BONDED OVERLAYS

Composite Block (Chopped Carbon Fiber):

- West System two-part epoxy (West System 105 Epoxy Resin + West System 206 Slow Hardener), 3:1
- Chopped carbon fibers
- Studs, at flanges only
- No debonding was observed; fatigue loading cracked tab plate and then crossframe multiple times, while the repair was in place. 4 mil+ cycles, at extremely high load levels






Bun, S., Bonet, E., Matamoros, A., Bennett, C., Rolfe, S., Barrett-Gonzalez, R. (2014). "Repair of Distortion-Induced Fatigue Damage in Steel Bridges using Composite Materials." Proc. European Bridge Conference, London, U.K.

DISTORTION-INDUCED FATIGUE – ADHESIVELY-BONDED OVERLAYS

Composite Block (Chopped Carbon Fiber):


Bun, S., Bonet, E., Matamoros, A., Bennett, C., Rolfe, S., Barrett-Gonzalez, R. (2014). "Repair of Distortion-Induced Fatigue Damage in Steel Bridges using Composite Materials." Proc. European Bridge Conference, London, U.K.

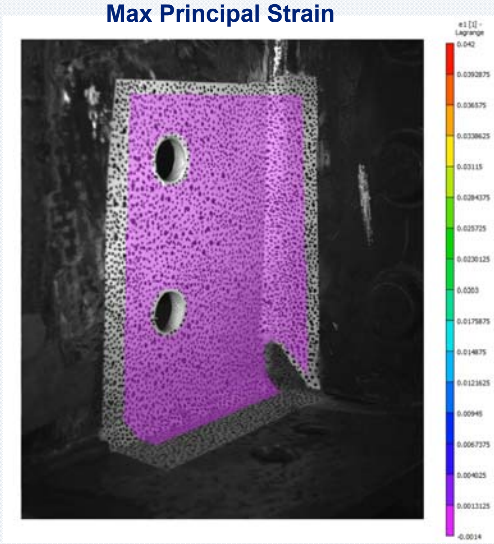
DISTORTION-INDUCED FATIGUE – ADHESIVELY-BONDED OVERLAYS



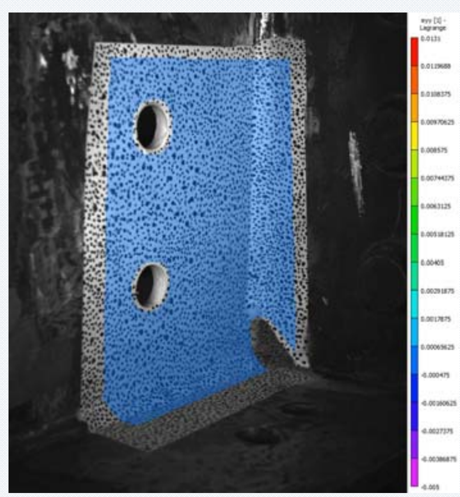

- Epoxy Resin = Epibond 420 A/B (manufactured by Huntsman); using a very thin bond layer
- The retrofit performance was examined for different crack patterns, up to a 6in. crack length.
- The retrofit has been applied with and without flange bolts and was effective in preventing distortion-induced fatigue crack propagation for all the tested pattern and lengths.
- No debonding has been observed in any of the fatigue trials

DISTORTION-INDUCED FATIGUE – ADHESIVELY-BONDED OVERLAYS

Max Principal Strain

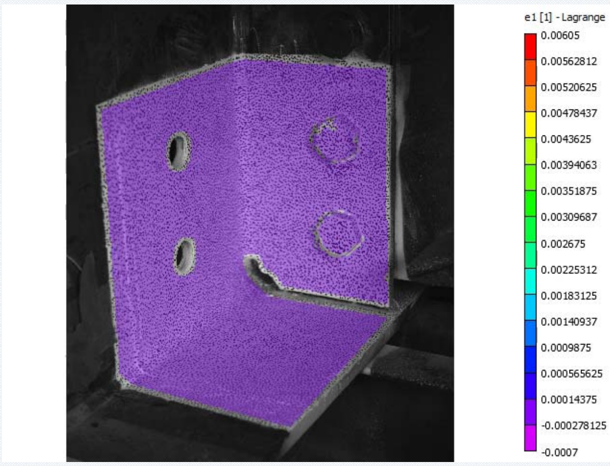


Strain in Y axis direction

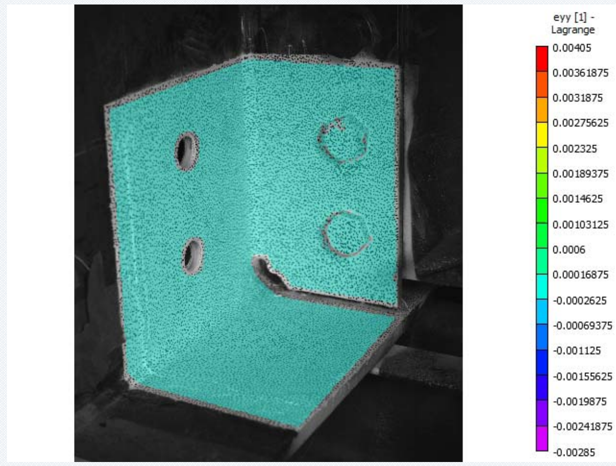


DISTORTION-INDUCED FATIGUE – ADHESIVELY-BONDED OVERLAYS

Max Principal Strain



Strain in Y axis direction



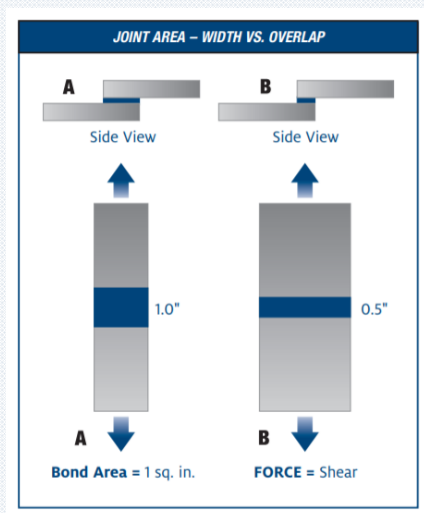
NEEDS FOR FUTURE WORK, SPECIFIC TO FATIGUE

- **Thickness ratio between bonded steel elements; limits of applicability**
- **Fatigue performance after environmental degradation**
- **Experimentation with different epoxies for different applications – i.e., overhead vs. vertical, etc.**
- **Very high-cycle fatigue loading**

Thank You

BEST PRACTICES

- Maximize shear and minimize peel & cleavage
- Maximize compression & minimize tension
- Joint width is more important than overlap



Source: Henkel website materials

DANIEL NAGATI, 2012

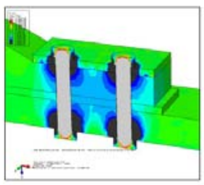


Figure 2-7: Section cut of curved overlay showing S33 stresses

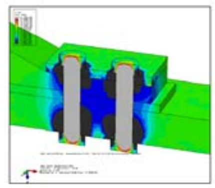


Figure 2-8: Section cut of ½-in. overlay showing S33 stresses

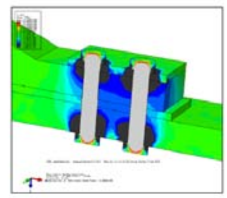


Figure 2-9: Section cut of overlay with closer bolt spacing showing S33 stresses

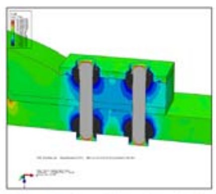


Figure 2-10: Section cut of specimen without a resin pool showing S33 stresses

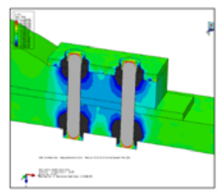


Figure 2-11: Section cut of specimen with 1-in. resin pool showing S33 stresses

DANIEL NAGATI, 2012

Table 2-1: Stresses at composite-resin/resin-steel interfaces for configurations analyzed

Configuration	Composite, MPa (ksi)	Resin, MPa (ksi)
Rectilinear overlay	-13.8 (-2)	10.3 (1.5)
Curved overlay	-11.7 (-1.7)	4.8 (0.7)
½-in. overlay	-30.3 (-4.4)	4.8 (0.7)
Closer bolt spacing	-26.9 (-3.9)	4.1 (0.6)
No resin pool	-11.7 (-1.7)	4.1 (0.6)
1-in. resin pool	-11.7 (-1.7)	0.5 (0.07)

DANIEL NAGATI, 2012

Highlights

- Configurations with thinner overlays showed the largest compressive stresses at the interface layer.
- Reducing the bolt spacing led to higher compressive stresses over a shorter region of the overlay.
- A resin pool of 25-mm (1-in.), extending from the edge of the composite, led to a significant reduction in the tensile stress at the edge of the resin-steel interface.

AISC/NSBA Structural Adhesives Workshop
August 13, 2019 – Chicago, IL

CFRP Reinforcing of Corroded Steel Beams

Matthew H. Hebdon, Ph.D., P.E.
Samuel Sherry, PhD Candidate
Virginia Tech

Motivation

- Bearing/Shear
- Flexural Capacity

Research Goals

- Restore strength of deteriorated bridge girders
  - Corrosion section loss
- Increase strength
  - Load rating for Special Haul Vehicles

VirginiaTech

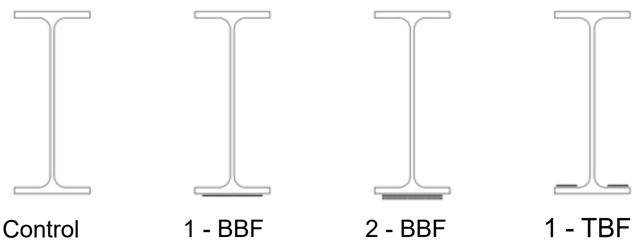
Girder Specimens

- VDOT supplied
- 7 Bridge girders
- Corroded bottom flanges

VirginiaTech

Girder Specimens

- Control girder (unreinforced)
- 3 CFRP configurations on bottom flange:
  - 1-BBF = 1 ply CFRP on bottom
  - 2-BBF = 2 plies CFRP on bottom
  - 1-TBF = 1 ply CFRP on top



Materials

- 2 types of carbon fiber systems:
  - Nippon RenewWrap Strand Sheet CF900/HM
    - Modulus of Elasticity: 92,820 ksi
    - Tensile Strength: 276 ksi
    - Elongation at Rupture: 0.30 %

  - Sika CarboDur S1012
    - Modulus of Elasticity: 23,930 ksi
    - Tensile Strength: 449 ksi
    - Elongation at Rupture: 1.69 %

Materials

- Nippon RenewWrap

- Sika CarboDur

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Invent the Future

Installation

- Both CFRPs installed per manufacturer's recommendations
- General procedure:
  - Sand blasted beams to white metal condition
  - Cleaned beams
  - Application of filler/priming adhesive
  - CFRP applied
  - Interface checked for "hollow" spots
  - Cured for 7 days prior to test

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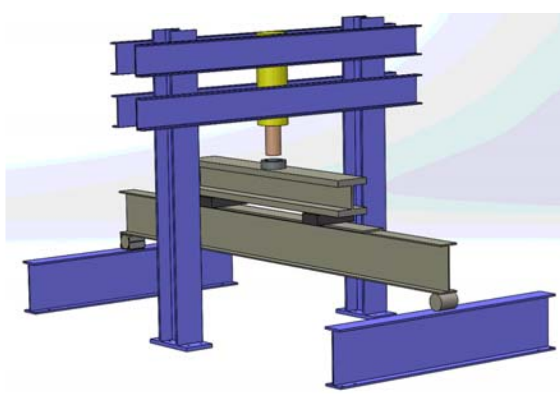
Installation

Test Setup

- 4 Point Bend Test
- 17 ft. Span
- 5.66 ft. Equal length segments



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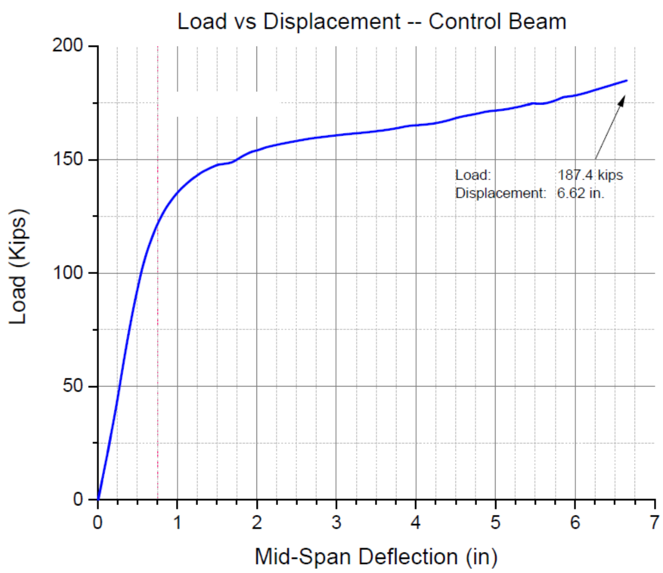
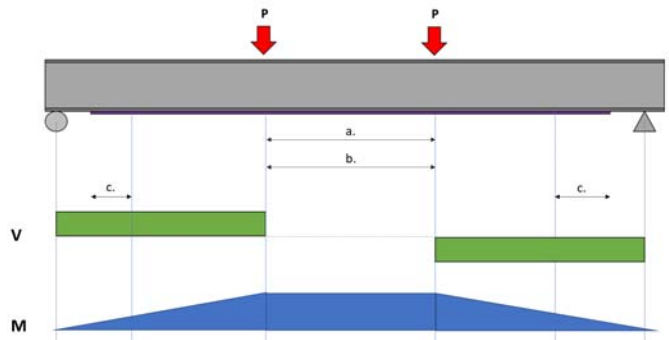
Control Beam

Control Beam



Failure Modes

- 3 Potential Failure Modes
  - a. CFRP Rupture
  - b. Intermediate debond
  - c. End debond



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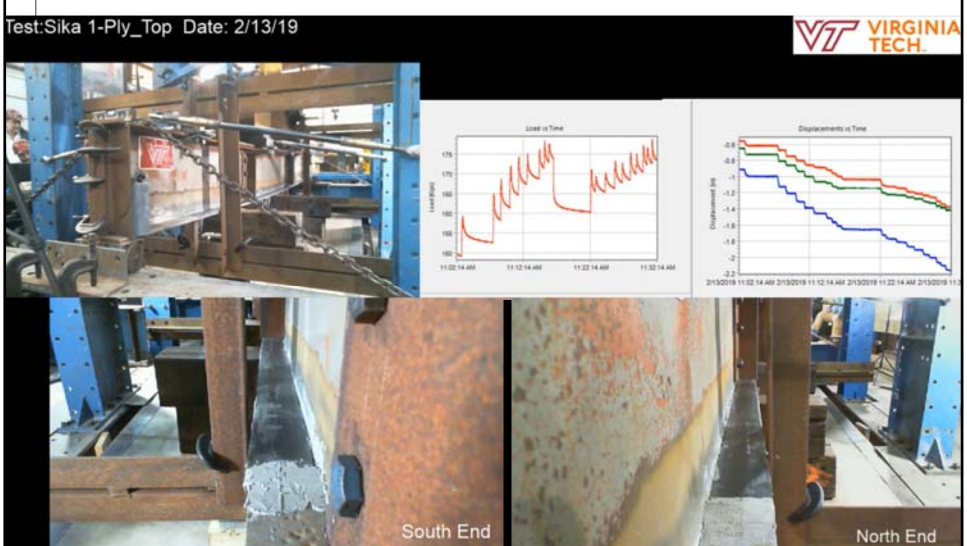
Sika 1-Ply TBF



Sika 1-Ply TBF

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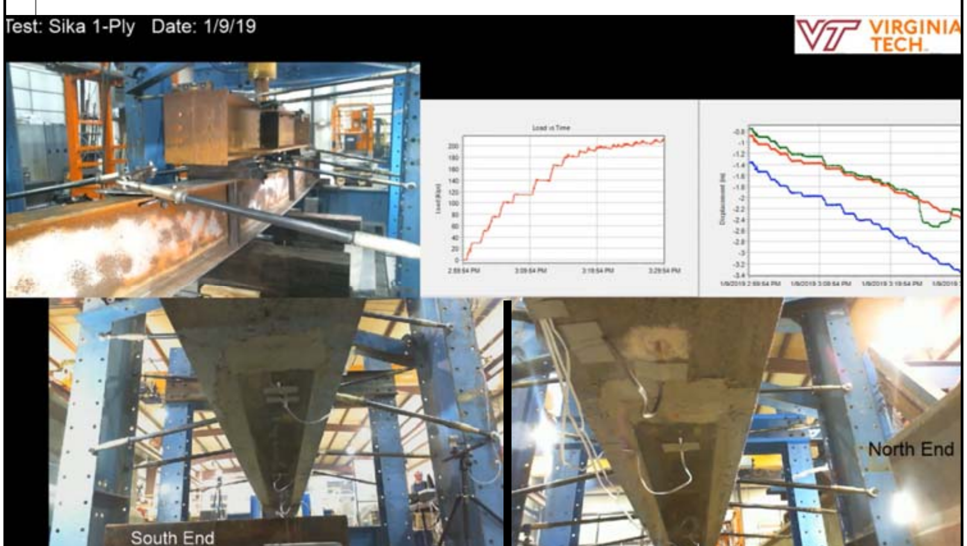
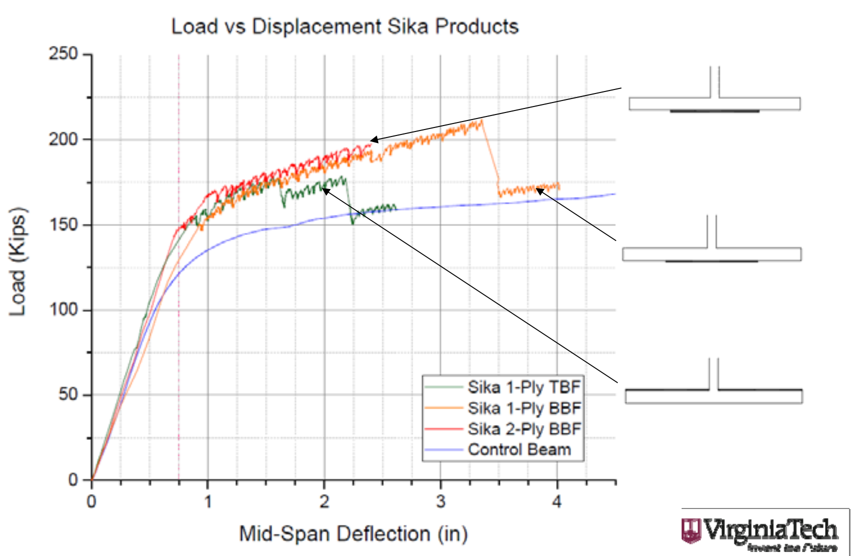
Sika 1-Ply BBF

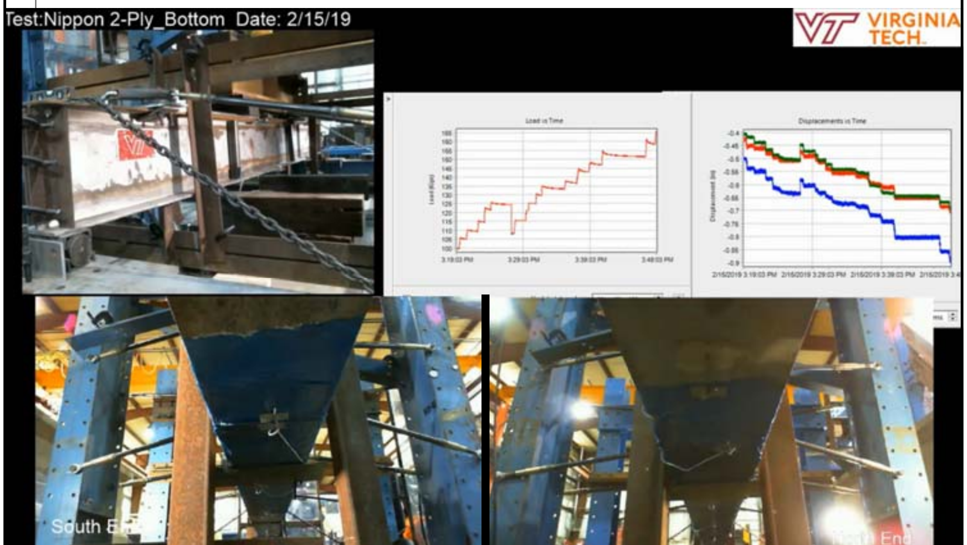


Sika 1-Ply BBF

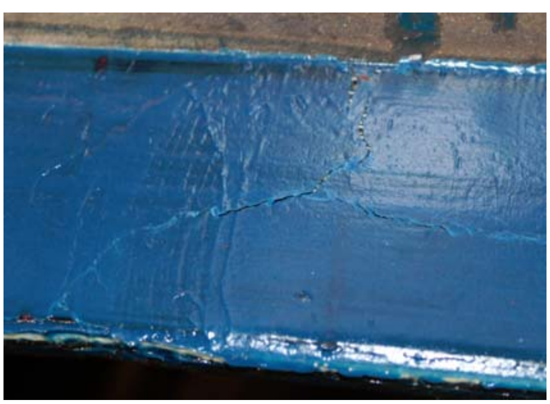
Comparison Sika Products

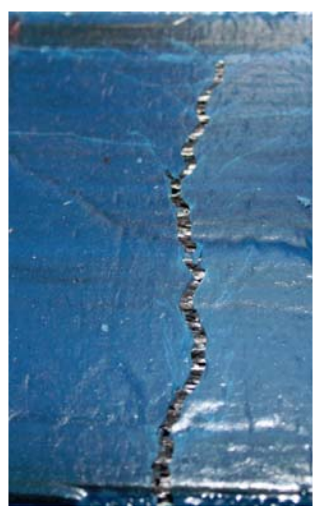


Nippon 2-Ply BBF

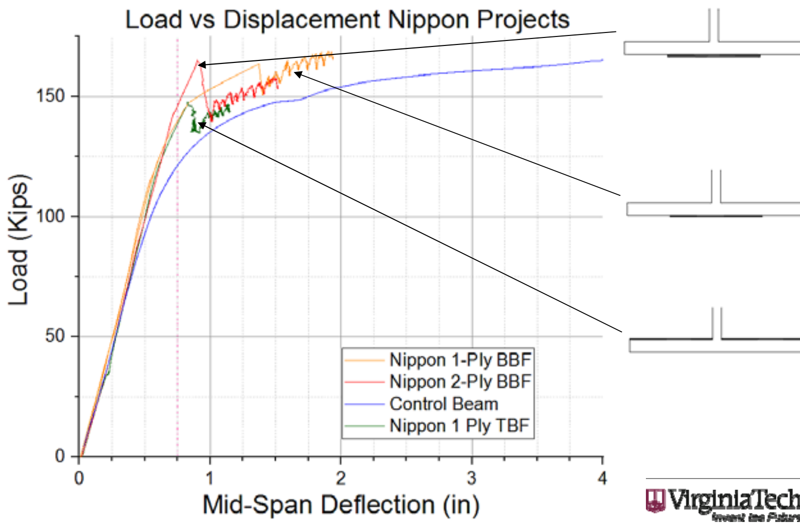


Nippon 1-Ply TBF

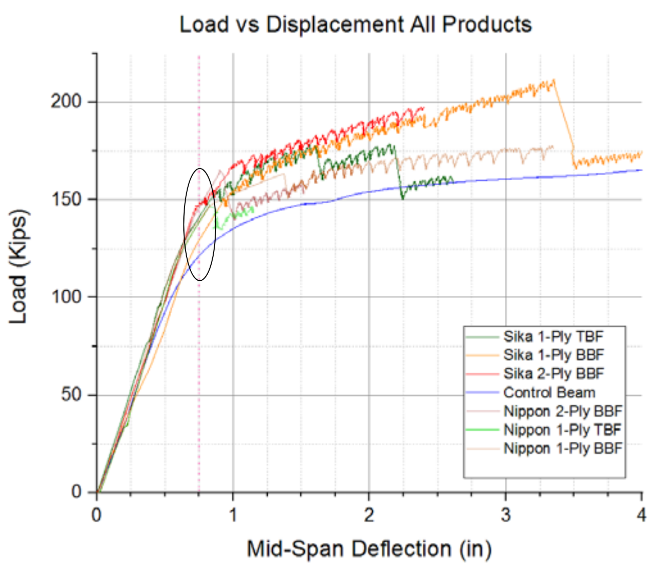




Comparison Nippon Products



Comparison All Products



Comparison All Products

Product	Location	# Plys	Failure	Load at .75" Displacement (kips)	% Increase
Control				123	
Nippon	BBF	1	CFRP Rupture	143.9	17.0
	BBF	2	CFRP Rupture	146.8	19.3
	TBF	1	CFRP Rupture	140	13.8
Sika	BBF	1	CFRP Rupture	130	5.7
	BBF	2	Local Flange Buckling / LTB	148	20.3
	TBF	1	Debond	141.8	15.28

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Small Scale Testing

24

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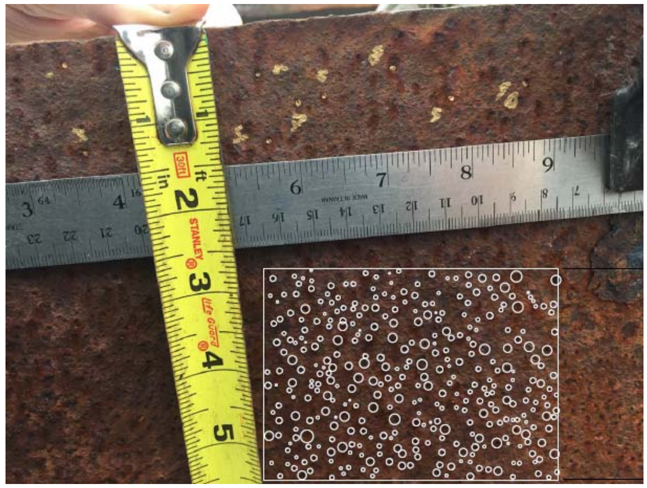
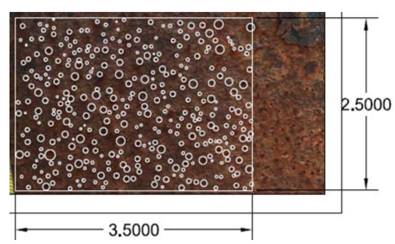
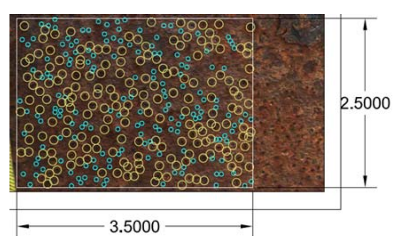
Small Scale Testing

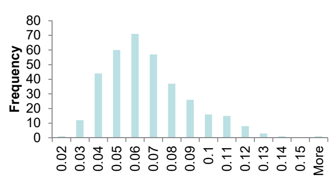


Small Scale Testing

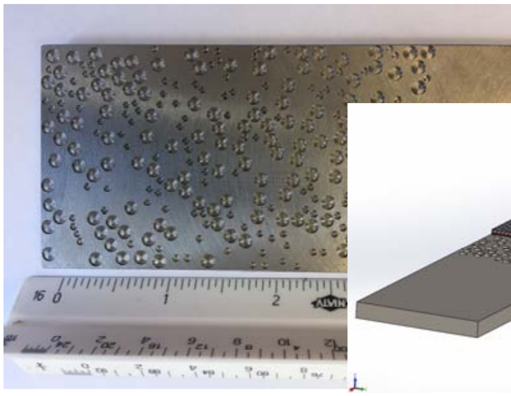
- Avg. dia. : 0.0662”
- Avg. dist. from centroids of closest pits: 0.1083”
- Count: 352

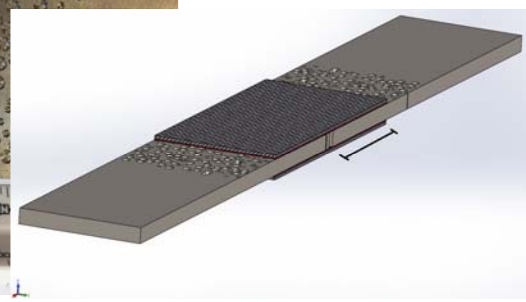






Small Scale Testing





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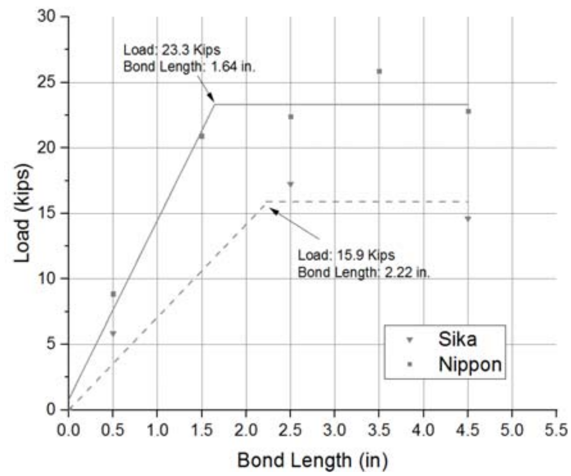
Small Scale Testing

- Double Strap Joint Specimens
  - 5 different bond lengths

Small Scale Testing

- Double Strap Joint Specimens



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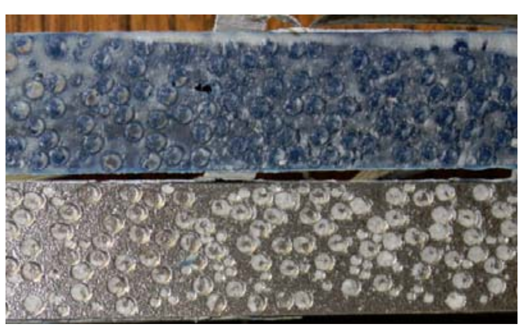
Small Scale Testing

- Double Strap Joint Specimens
- Minimal impact on bond length from corrosion



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Results

- Flexural strengthening of beams
  - Design for 3 failure modes: rupture, intermediate debond, end debond
  - Ductility of system is based CFRP strain limits
  - Multiple layers of CFRP is not additive
- Non-uniform surface profile
  - Preliminary*: Corrosion profile studied had little impact on bond length

Next Steps

- Adhesion on non-uniform surface profile
  - 4 varying levels of section loss
  - Surface preparation method
- Durability of CFRP on steel
  - In-situ testing
  - Accelerated testing
- Live load tests
  - Flexural strengthening
  - Beam end repair

Questions?

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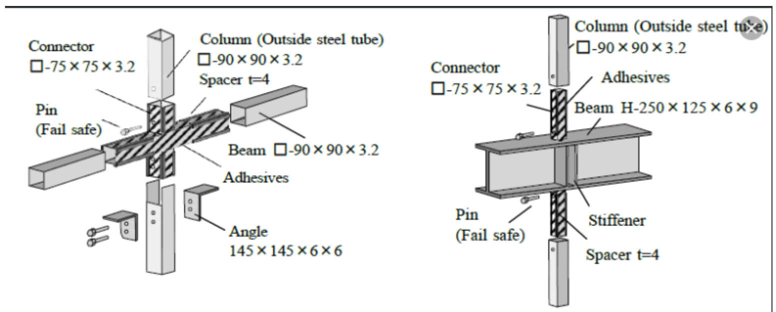
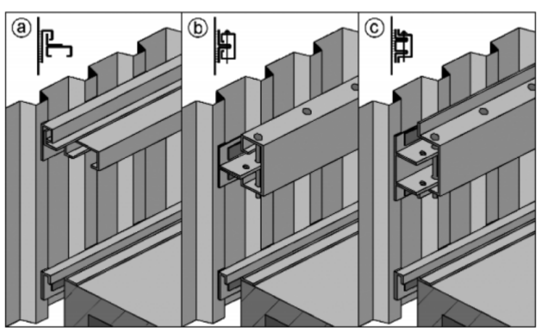
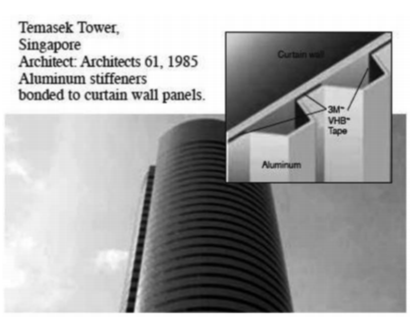
References:

- "Renewwrap® installation manual." (2018).
- Schnerch, D., and Rizkalla, S. (2008). "Flexural Strengthening of Steel Bridges with High Modulus CFRP Strips." *Journal of Bridge Engineering*, 13(2), 192–201.
- "Sika CarboDur ® System." (2014).

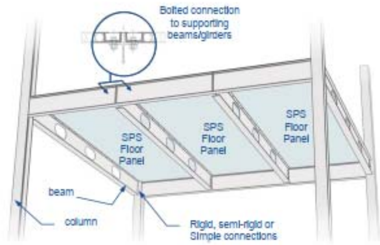


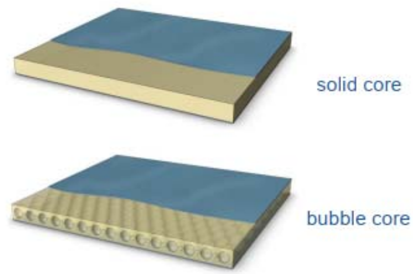
(a) Steel square tube beam (b) H-shaped beam





What are SPS Floors?





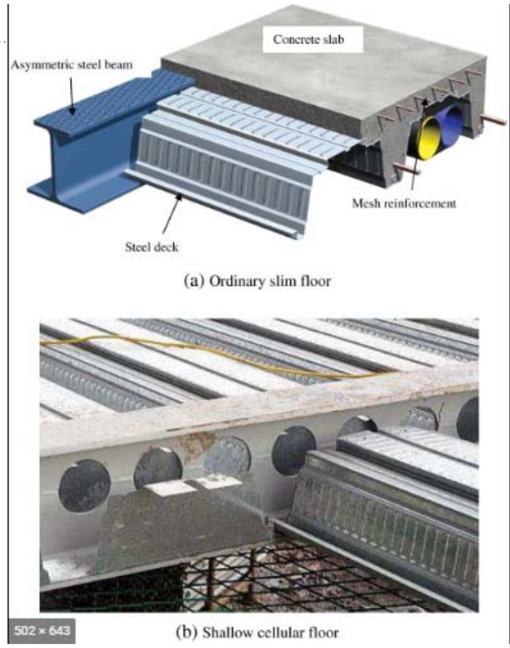
SPS Floors

- a composite floor panel made of two steel plates, a polyurethane core and a steel perimeter bar or profile
- bolted together to the top flange of the structural steel beams; generally made composite with secondary beams
- prefabricated factory quality construction with close dimensional tolerances
- proven and approved global technology

Core Configuration

- **Solid Core**: thin floor plates with a compact solid polyurethane core between faceplates
- **Bubble Core**: hexagonally closely packed air-filled polypropylene spheres with diameter equal to core thickness (deeper and stiffer core allowing longer spans while remaining lightweight)

March, 2015 Exhibit 5 SPS



(a) Ordinary slim floor

(b) Shallow cellular floor

AISC's ongoing research projects vary in size and scope. Here's an inside look at what we're doing to improve steel design and construction.

Revealing Research

BY DEVIN HUBER, PE, PHD

Devin Huber (**huber@aisc.org**) is AISC's director of research.

AS YOU THUMB THROUGH your AISC *Manual*, *Specification*, or one of our dozens of Design Guides, do you ever wonder how we got so far in understanding how to design with, fabricate, and ultimately build with structural steel?

Or have you read an article in this magazine about some new innovative product or process and thought, "How did they come up with that?" The answer always starts with an idea or ideas and is followed by research to figure out not only how it can work, but where it can be applied and who it will benefit.

AISC has been conducting research for almost as long as we have been an organization (which is nearly a century, if you're counting). Sometimes we are working on topics that will be incorporated into future versions of the *Specification*, so the end user may not be fully aware of what we have been looking at until they are using it in day-to-day practice. Other times our research is more related to an innovation that has potential to help increase structural steel's market share or transform an existing idea or application. And oftentimes AISC joins up with other organizations such as the Charles Pankow Foundation, ASCE or NSF to co-fund work to allow our dollars to go further in getting a particular topic more fully developed.

Below is a brief overview of our research initiative, including its basic setup, how ideas are developed, clarity on timelines related to funding projects, and how we disseminate results of our various projects. Finally, I'll also shed some light on a few ongoing AISC research projects to provide an overview of the types of research we conduct.

Research Q&A

First, we'll answer a few common questions about AISC's research program.

How much money does AISC spend on research and how many projects are currently funded?

Every year, AISC generally spends more than $1 million on research endeavors. This helps to support the 20-plus research programs we are either fully funding or jointly funding with other organizations.

Where can I see the results of AISC's Research?

Quite simply, the results of our research endeavors can be seen everywhere, ranging from specifications and standards to the application of certain techniques in structural steel design, fabrication, and erection. More specifically, our research results are shared or incorporated into:

- AISC Research Reports (**aisc.org/research**)
- Peer-reviewed journal articles, including those found in *Engineering Journal*
- AISC specifications
- AISC Design Guides
- Specifications developed by other organizations, such as AASHTO, AWS, etc.

Who decides what to fund for research?

Both AISC staff and the AISC Committee on Research help determine which projects will be funded.

I have an idea! How can I submit it for potential research funding?

In general, we accept both unsolicited proposals and Research Needs Statements (RNS) and also solicit for proposals as needed. Read on for more details on how to submit a proposal.

AISC Research: Who We Are

The AISC Research program consists of AISC staff, primarily me (the director of research), and also a 26-member Committee on Research (COR). The makeup of the COR includes practicing engineers/practitioners, fabricators, erectors, academic researchers and even steel product producers.

The COR meets face-to-face twice a year, once in October and once in April, just ahead of NASCC: The Steel Conference, and also holds periodic conference calls. The intent of these meetings/discussions is to bring forth emerging topics affecting the structural steel industry needing research, discuss ongoing research, review received proposals or RNS, and ensure the AISC stays aligned with the broader industry in funding research endeavors.

Topics and Timelines

When it comes the question of how topics are chosen, again, AISC accepts both solicited proposals that are developed with the help of the COR and unsolicited research proposals. AISC solicited calls for proposals get sent out as needs arise and topics are developed that the COR and AISC feel need to be further investigated via a research endeavor. Many of these needs are requested by AISC's Committee on Specifications to help to improve our *Specification for Structural Steel Buildings* (AISC 360).

Unsolicited research ideas come in the form of an RNS or a fully developed proposal. An RNS is a brief document (typically two to five pages) highlighting a structural steel-related topic that an interested party feels should be researched, with the submitter either willing to perform the research themselves with AISC funding or simply suggesting an idea for AISC to further develop and potentially consider for research. An RNS allows *anyone* in the industry to put forth an idea.

Full proposals, solicited or unsolicited, are generally submitted by the party intending to do the research, and are typically far more detailed then an RNS, systematically laying out how the research will be conducted and disseminated. More information and templates for both RNS and full proposals are available via at **aisc.org/research**.

In order to adhere to our scheduled COR gatherings, and in alignment with AISC budgets being set on a calendar year, the latest a proposal/RNS can be received an be considered for following in the subsequent calendar year is, in most cases, August 31. However, it should be noted that budgeted activities begin around July of the current year in preparation for the following year's budget. Hence, getting proposals in hand to review ahead of the spring COR (deadline of February 28) meeting is helpful in getting them approved for the following year.

Rainier Square Tower in downtown Seattle, the first building to use the SpeedCore system.

A SpeedCore prototype specimen being tested for behavior under axial and wind loading at Purdue University.

Current Research

So what are we working on currently? As a matter of fact, we are involved in a multitude of ongoing projects. We've highlighted a few here to give you an idea of the breadth and depth of work we fund and support.

SpeedCore
Current research being led by Amit Varma, Purdue University and Michel Bruneau, University of Buffalo

If you have been paying attention to this publication recently—and any others covering structural steel—you have likely heard of the SpeedCore system. First used by structural engineer Magnusson Klemencic Associates (MKA), this innovative structural system uses plain concrete sandwiched between exterior steel plates acting compositely with the concrete to form a robust structural system that can be used as the building core in mid- to high-rise steel structures. And the first real-world application of the system, Rainier Square Tower in Seattle (also designed by MKA and fabricated by AISC member Supreme Steel), is currently ongoing.

While this is the first full-scale implementation of the system, it has been the subject of research studies for several years by both AISC and the Charles Pankow Foundation. In fact, these "sandwich" panel systems have been used in several different applications previously, most notably in the nuclear industry as containment structures. But Rainier Square Tower is the first use of SpeedCore as the core system in a high-rise building.

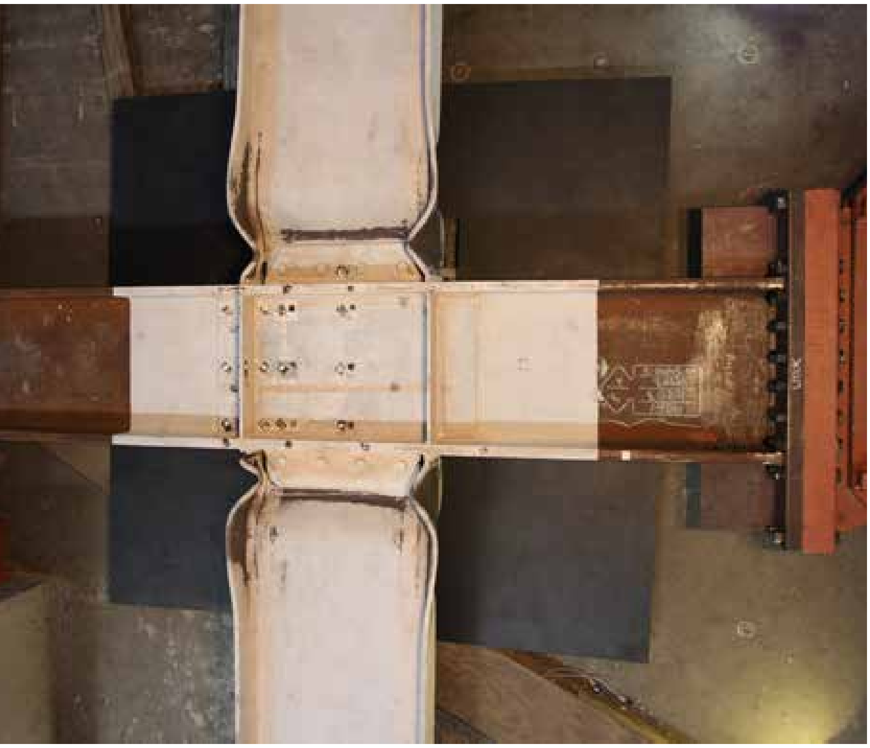
For the current application in building cores, some of the first published research came out in 2009 and since then, several AISC co-funded research endeavors have helped to further develop and refine the system such that it is now demonstrated as feasible for use in steel construction. Further, the research done to date has helped establish key structural behavior of the system and has helped establish an R = 8 for the systems when used in seismic areas, which is the best value that can be obtained when using it as a seismic lateral force-resisting system.

Weld Design Requirements in Continuity Plates and Doubler Plates for Moment Frame Applications
Current research being led by Chia-Ming Uang, University of California-San Diego

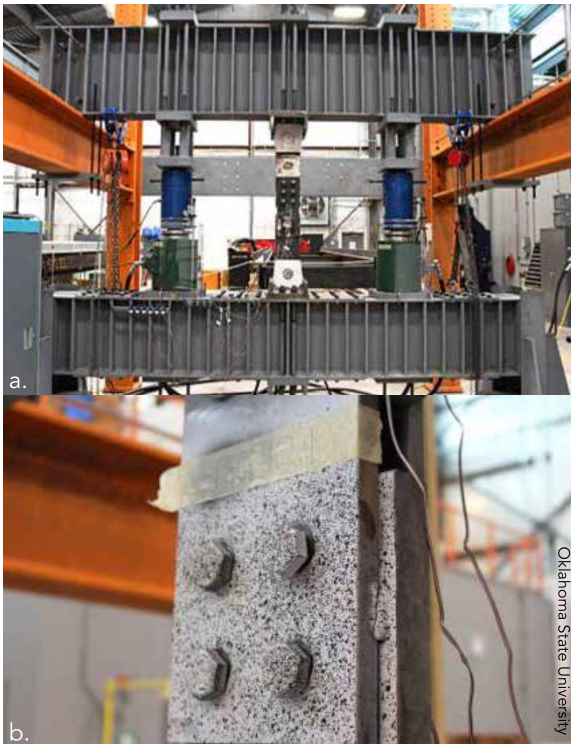
The intent of this AISC-funded research is to experimentally investigate potential design and construction efficiencies for both continuity plates and doubler plates used in special moment frame (SMF) connections.

As is currently written in the AISC *Seismic Provisions for Structural Steel Buildings* (AISC 341-16), the weld that connects the continuity plate to a column flange in a welded beam-column connection in an SMF is required to be a complete-joint-penetration groove weld. Similarly, the use of doubler plates in conjunction with continuity plates can be challenging to fabricate as the groove or fillet welds connecting the doubler plate to the column are required to develop the design shear yielding strength of the doubler plate thickness.

The use of groove welds in these applications, or very large fillet welds in doubler plates, leads to time-consuming connection details from both a detailing and construction/fabrication aspect. Additional constraints on fillet weld thicknesses and stability limits can make these connections very challenging to fabricate.



A moment connection specimen being tested at the University of California-San Diego by Chia-Ming Uang and Mathew Reynolds to determine if fillet welds can be used in lieu of CJP welds in SMF connections.



Overall setup for testing combined bolt and weld specimens (a) and a close-up of the tested specimen (b) at Oklahoma State University.

This research is investigating ways to economize the detailing, and subsequent fabrication, of continuity and doubler plates. One item being investigated is the use of fillet welds for the continuity plate-to-column flange weld connection. Another item being considered in the research is to provide a design methodology to size the weld in doubler plate applications for the proportion of the panel zone shear that is actually required. These approaches, if shown to be adequate, will challenge conventional design approaches but could yield a more efficient design in the process. Also, the required weld capacity for both doubler plates and continuity plates will be generated from a consistent set of seismic demands. This research is partially completed and is in its second (and final phase) of testing along with ongoing analytical studies. The first testing phase looked at one-sided moment connections, while the second phase focuses on two-sided moment connections, or an interior beam-column connection. To date, results appear promising that a proposed reduction in welding can be realized; however, this cannot be confirmed until all testing and analyses are complete and results have been reviewed by an AISC oversight committee. Ultimately, any changes to AISC *Seismic Provisions* would need to be balloted and approved per approved processes.

Understanding the Behavior of Steel Connections with Bolts and Welds in Combination
Current research being led by Mohamed Soliman, Oklahoma State University

This project focuses on investigating the behavior of steel connections with bolts and welds sharing the load. The use of bolts and welds in combination may occur during the construction phase of a project. The need to combine bolts and welds can occur if the design load changes, when there are unforeseen difficulties in the make-up or matching of bolt holes, or when retrofitting existing structures.

As is currently understood, a welded connection possesses relatively small capacity for deformations when reaching maximum strength and slip critical bolted connections remain stiff during loading. Therefore, the structural engineering community remains skeptical about these combination connections due to the uncertainty regarding deformation capacity of both welded and bolted connections.

The current research endeavor at Oklahoma State University is an extensive experimental program involving more than 100 specimens and also uses complex analytical tools to help fully understand the behavior of combined bolt and weld connections. The overarching goal of the project is to provide design guidance for realistic configurations of connections employing bolts and welds that may exist in steel buildings and bridges and to provide the structural engineering community the necessary tools to design, and understand the behavior of bolted connections supplemented by welds.

This project is ongoing and is in its second and final phase of testing. The first phase of testing focused on concentrically loaded specimens, while the second phase is focusing on eccentrically loaded specimens. So far, the results seem to indicate there may be more capacity in combined bolted and welded connections then what current AISC provisions calculate. However, these results are still being analyzed and any final recommendations will subject to review and formal balloting procedures for any implementation into future versions of the AISC *Specification*.

Current AISC Research Projects

Project Title	Principal Investigator(s)	Affiliated Organization/ University	Funding Partners
Advancing Performance-Based Structural Fire Engineering Design in the U.S. through Exemplar Procedural Guidance	Kevin LaMalva	ASCE	Charles Pankow Foundation ASCE MKA Foundation
Analysis and Design of Eccentric Stiffeners in Moment Connections to Column Flanges	Keith Kowalkowski	Lawrence Technological University	AISC solely funded
Bearing and Tearout of Bolted Connections	Mark Denavit	University of Tennessee, Knoxville	AISC solely funded
Behavior of Steel Connections with Bolts and Welds in Combination	Mohamed Soliman Bruce W. Russell	Oklahoma State University	AISC solely funded
Comprehensive Revision of Design Considerations for Column Base Connections in Steel Moment Frames	Amit Kanvinde	University of California, Davis	Charles Pankow Foundation
Evaluating and Fixing a Potential Fracture Problem with Extended Stiffened End-Plate SMF Connections	Matthew Eatherton Tom Murray	Virginia Polytechnic Institute and State University	AISC solely funded
Extra-Long Slots for Slip-Critical Bolted Joints	Gian A. Rassati James A. Swanson	University of Cincinnati	AISC solely funded
Fillet Weld Size and Length Effects	Bo Dowswell	ARC International	AISC solely funded
Fundamental Evaluation of the Lateral-Torsional Buckling Resistance of Welded I-Section Members	Don White	Georgia Tech	Metal Building Manufacturers Association (MBMA) American Iron and Steel Institute (AISI)
Investigation into Shear Stud Fatigue Demands: Towards Modification of the Existing AASHTO Stud Fatigue Provisions	Gary Prinz	University of Arkansas	AISC solely funded
Pre-Standard for Performance-Based Design for Wind	Donald Scott	ASCE	Charles Pankow Foundation ASCE
Skewed T-Welds	Bo Dowswell Fouad H. Fouad	University of Alabama at Birmingham	AISC solely funded
Steel Diaphragm Innovation Initiative (SDII)	Benjamin Schafer Matt Eatherton Jerry Hajjar	Johns Hopkins University Virginia Polytechnic Institute and State University Northeastern University	AISI MBMA Steel Deck Institute (SDI) Steel Joist Institute (SJI)
Qualification Testing for Artifacts in the Protected Zone	Matthew Hebdon Matthew Eatherton	Virginia Polytechnic Institute and State University	AISC solely funded
Parametric Investigation of Chevron Braced Frames	Charles Roeder	University of Washington	AISC solely funded
Seismic Performance Assessment of Steel Multi-Tiered Ordinary Concentrically-Braced Frames	Larry Fahnestock	University of Illinois	AISC solely funded
Seismic Stability Design of Steel Frames	Larry Fahnestock	University of Illinois	AISC solely funded
Seismic and Wind Behavior and Design of Coupled Concrete-Filled Composite Plate Shear Walls (CF-CPSW) Core Walls (SpeedCore) for Steel Buildings	Amit Varma Michel Bruneau	Purdue University University at Buffalo	Charles Pankow Foundation
Performance Based Structural Fire Engineering of Buildings with CF-CPSWs (SpeedCore)	Amit Varma	Purdue University	Charles Pankow Foundation Steel Institute of New York
R-Factors for Coupled Composite Plate Shear Walls – Concrete Filled (Coupled-C-PSW/CF, SpeedCore)	Amit Varma Michel Bruneau	Purdue University University at Buffalo	Charles Pankow Foundation
Weld Design of Continuity and Doubler Plates for IMF and SMF	Chia-Ming Uang	University of California, San Diego	AISC solely funded

Advancing Steel

Ultimately, the goal of our research endeavors at AISC is to advance the structural steel industry through a variety of studies that cover a breadth of topics. We strive to stay a step ahead and make sure the industry and our members are equipped with the most sound and forward-thinking technical solutions to the infinite number of challenges associated with structural steel design and construction. Visit **aisc.org/research** for more on our research initiative, including information on submitting proposals and reviewing AISC Research Reports. ■

The Milek Fellowship

One portion of our research program that stands alone from other projects/proposals is the annual Milek Fellowship (formerly the AISC Faculty Fellowship) for which AISC selects a promising young non-tenured university faculty member. The award was renamed for William A. Milek Jr., AISC's former vice president of engineering and research, in recognition of his invaluable contributions to AISC and the structural steel industry as a whole. The award provides the fellow with $50,000 a year for four years to perform their research. The deadline for submitting a proposal for the Milek Fellowship is between August 31 and September 15 of the current year, with funding to commence in the following year. Visit **aisc.org/milek** for more information as well as a list of all past fellowship recipients

Active AISC Milek Fellowships

Project Title	Principal Investigator(s)	Affiliated Organization/ University
Thin Composite Two-Way Flooring Systems for Steel Structural Systems	Will Collins	University of Kansas
Performance-Based Design of Passive Fire Protection for Floor Systems in Steel-Framed Buildings	Spencer Quiel	Lehigh University
Seismic Performance of Moment Resisting Frames with Fuse-Type Connections	Patricia Clayton	University of Texas at Austin
Steel Seismic Systems with Architectural Flexibility	Gary Prinz	University of Arkansas
Inelastic Design for Steel Structures Subjected to Wind Loads	Johnn P. Judd	University of Wyoming

DIAMANT The Metalplastic Company

Time and Cost Saving Assembly in steel construction

MM1018 the liquid shim plate

The problem …

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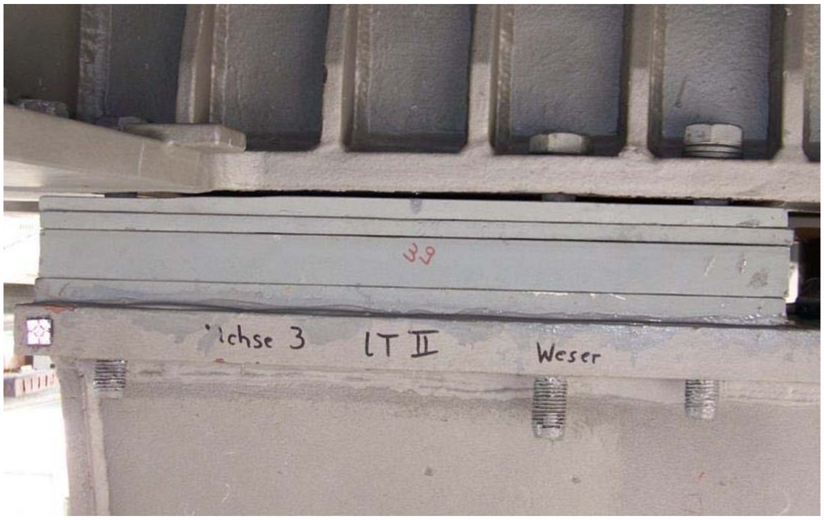


Gap situation after traditional use of shim plates

How do gaps in steel constructions arise?

- Failures and tolerances during the manufacturing process
- Welding distortion through heat
- Planning or design errors
- Assembly imprecision
- Interface areas

Gaps in steel construction can hardly be avoided

Conventional measures

- Insert wedges
- Insert stiffeners
- Close the gap by welding
- Fill with silicones, mortar or cements or other non approved products

Disadvantages

- No full-surface support
- Corrosion protection gets damaged
- Time-consuming, machining required

Conventional shim

DIAMANT The Metalplastic Company

Solution

DIAMANT The Metalplastic Company

Zero gap after use of DIAMANT MM1018 liquid shim plate

MM1018 – The liquid shim

DIAMANT
The Metalplastic Company

DIAMANT
The Metalplastic Company

DB NETZE

WSV.de
Wasser- und
Schifffahrtsverwaltung
des Bundes

RAG
Deutsche Steinkohle

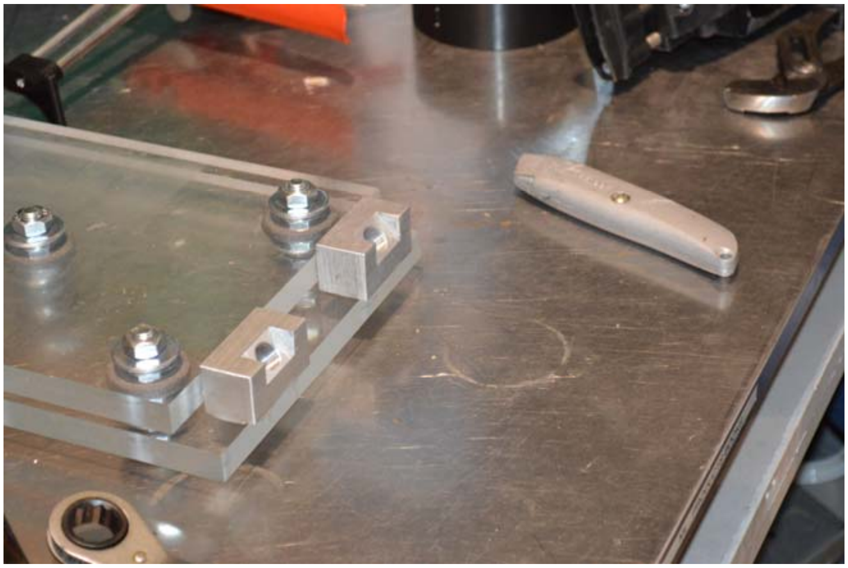
MM1018

AbZ
DIBt

Z-3.82-2042

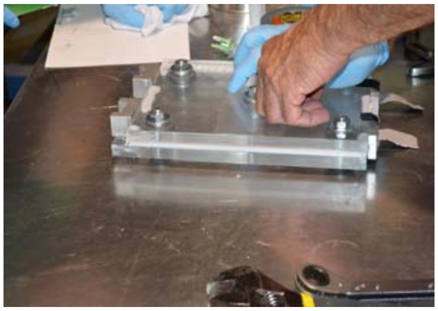
ABS
TYPE APPROVED PRODUCT

DIAMANT **MM1018** the only approved material for gap compensation of **steel-to-steel connections**



How does it work?   Start with two plates that have an air gap   Glue on Injections caps

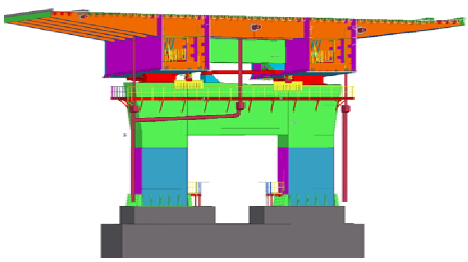
Then seal all the open seals with specal sealer.

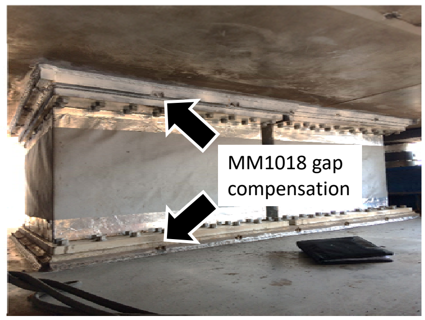


Add the injectors and vent connections to the part

Ideal for restoration…

But also for new constructions





The MM1018

- 100% form and force fit
- Always a perfect match – The liquid shim plate
- NO machining
- Compressive strength up to 160 N/mm²
- Gap up to max. 140 mm (abz up to 10 mm)
- Corrosion protection for flange areas

MM1018 liquid *product number 1866*

Highly filled metal polymer with liquid viscosity

- Injection and ventilation points required
- Circumference sealing of flange area
- Care for screw protection

MM1018 liquid *product number 1866*

Injection of MM1018 FL

- Clean surface and apply DIAMANT separator (if required)
- Aplly injection and ventilation points
- Circumference gap seal with MM1018 rapid
- Mix and inject MM1018 liquid
- Cure MM1018, then apply load

MM1018 putty *product number 1436*

Application of MM1018 P

- Clean surface and apply DIAMANT separator (if required)
- Mix and apply MM1018
- Join surfaces and fix in position
- Remove surplus material
- Cure MM1018, then apply load

MM1018 putty *product number 1436*

Highly filled metal polymer with putty viscosity

- Disassemble flange areas
- Sufficient space to apply material

Your benefits

- ✓ Cost savings
- ✓ Time savings
- ✓ Flexibility
- ✓ On site application, no big equipment
- ✓ Full-Service (product + application)
- ✓ Experience by **more than 1.000 applications**



The Beginning …

South Bridge, Cologne (1993) – bearing replacement


Reference
after 10 years
In service



Typical Railway Applications

DB NETZE

DIAMANT The Metalplastic Company

Noice reduction walls

Building construction

Signal pilons

Bearing installation

Broken rock walls

Steel flange connections

Bearing installation with MM1018

DIAMANT The Metalplastic Company

Bearing installation at Izmit Bay Bridge, Turkey 2016

2,7km long highway bridge, Earthquake area

Special solutions become possible

Bearing installation with MM1018

Lennetalbrücke, NRW road bridge (2016)
Gap compensation with MM1018 liquid

ZSB Zwickauer Sonderstahlbau GmbH

HOCHTIEF

Straßen.NRW. Landesbetrieb Straßenbau Nordrhein-Westfalen

mageba

Bearing installation with MM1018

The Metalplastic Company

Bearing installation with MM1018

The Metalplastic Company

Bearing installation with MM1018

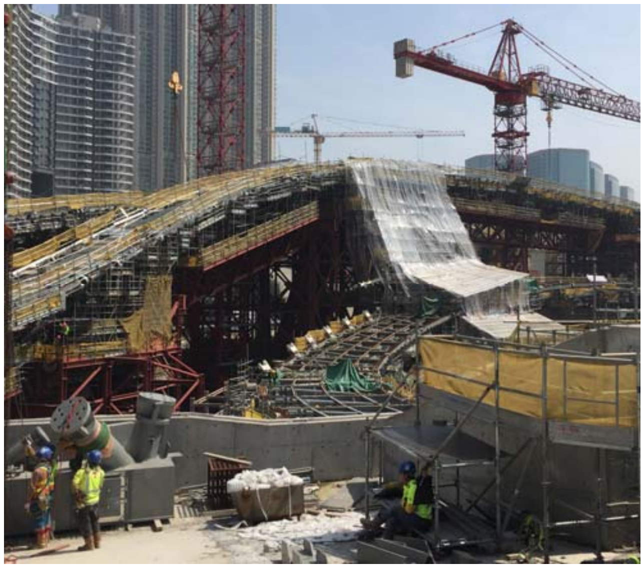
HongKong, Kowloon Express Rail Link Station

Bearing installation at
World's Largest Underground High-Speed Rail Station

VSL

mageba Switzerland www.mageba.ch

MTR




mageba

HongKong, Kowloon Express Rail Link Station

2 jobs with 2 German engineers (Dec. to Feb. 2016)

Total working days = 12

Force fit installation of 18 bearings!!

Largest bearing was 82 Inches X 70 Inches

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A1 Lützelmurgviadukt

Fingerübergang RSFD-KF200

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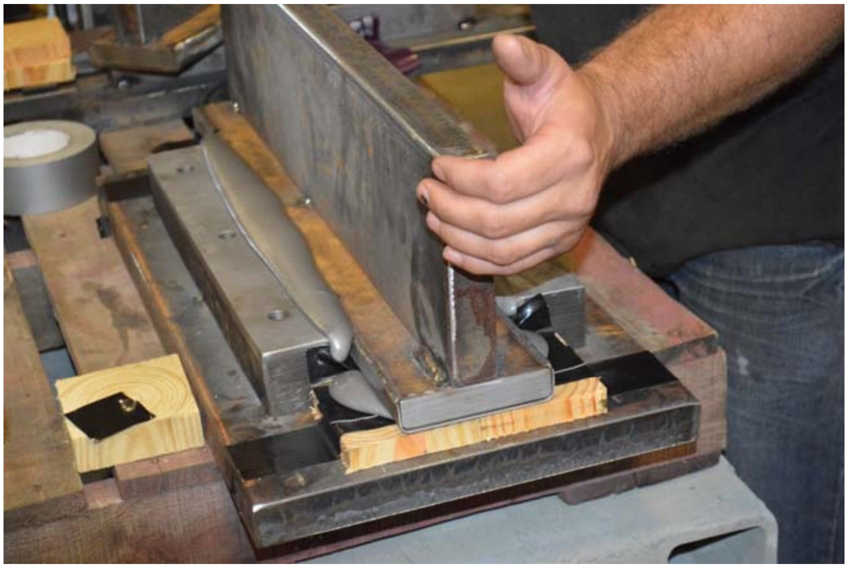


Setting up trial part for expansion joint test - D S Brown

Test - Expansion Joint Used on Gerald Desmond Bridge Long Beach, CA

Sanierung Portalkran P2

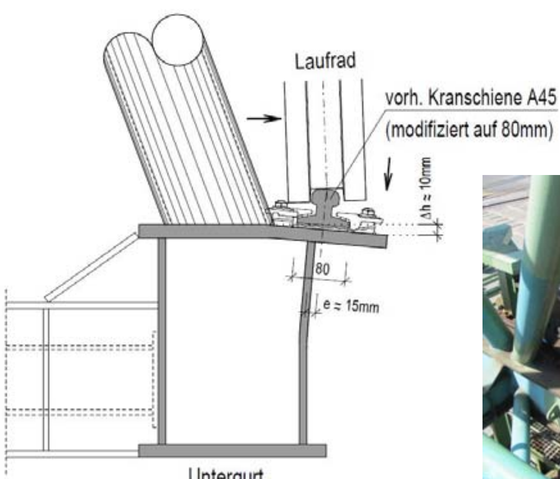
Kraftschlüssiger Spaltausgleich an 180m Schienenauflage

SALZGITTER MANNESMANN LINE PIPE
Ein Unternehmen der Salzgitter Gruppe

WERNER Bauingenieure

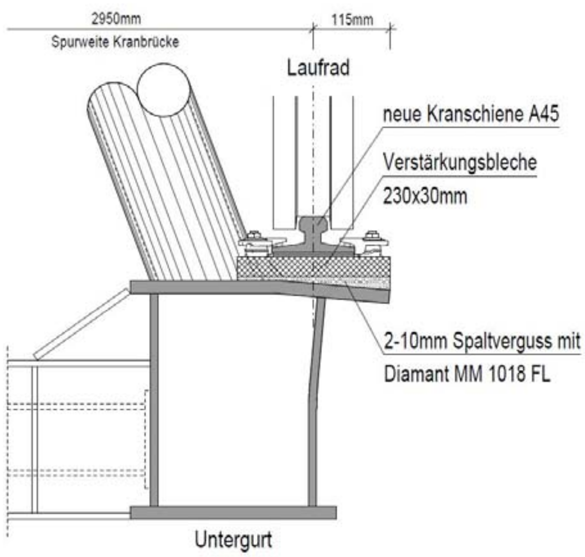
PRAGER GmbH Sachverständigenbüro

Aufgabenstellung



Situation zur Verdeutlichung überspitzt dargestellt. Der Istzustand wich von dieser Darstellung ab.

Konzept



Installation

Kranschiene vor der Instandsetzung

Installation

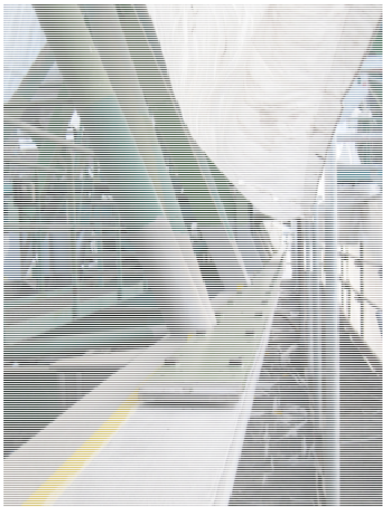
Ausbau der alten Fahrschienen

Installation

Sandstrahlen und Grundierung

Installation

Vergussvorbereitung



Installation

Vorbereitungen für Injektion abgeschlossen

Installation

Injektion abgeschlossen – Rückmusterdeckel für Qualitätssicherung

Installation

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Fertige Installation mit neuer Schiene und Korrosionsschutz

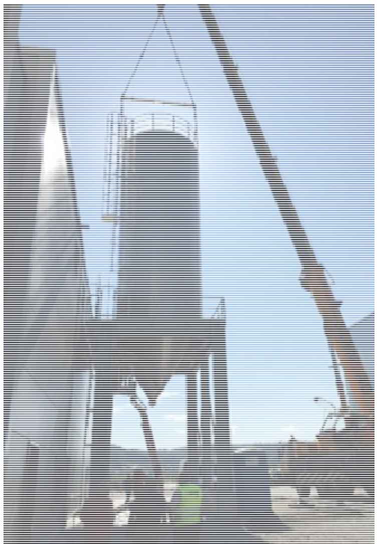
Erection of silos

Switzerland (2015)
Gap compensation with MM1018 putty

Erection of silos

Erection of silos

DIAMANT The Metalplastic Company

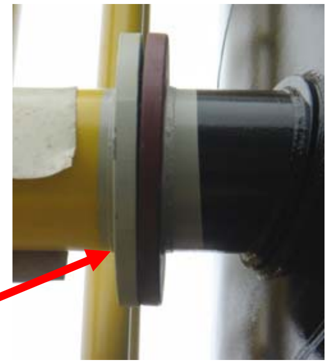


Offshore applications

DIAMANT The Metalplastic Company

G&G International, Belgien (2013) – Spaltausgleich Flanschbereich

Offshore applications



Split between the Joints of
the tower and piping
Sealed with MM 1018

Offshore applications

Heavy foundations

DIAMANT
The Metalplastic Company

Power plant, Walsum (2008) Foundation for air heater (12tons)

Steel Support foundations

DIAMANT
The Metalplastic Company

BV carpark Zürich – column stand 2015
Gap compensation on column stands

Marti Gruppe

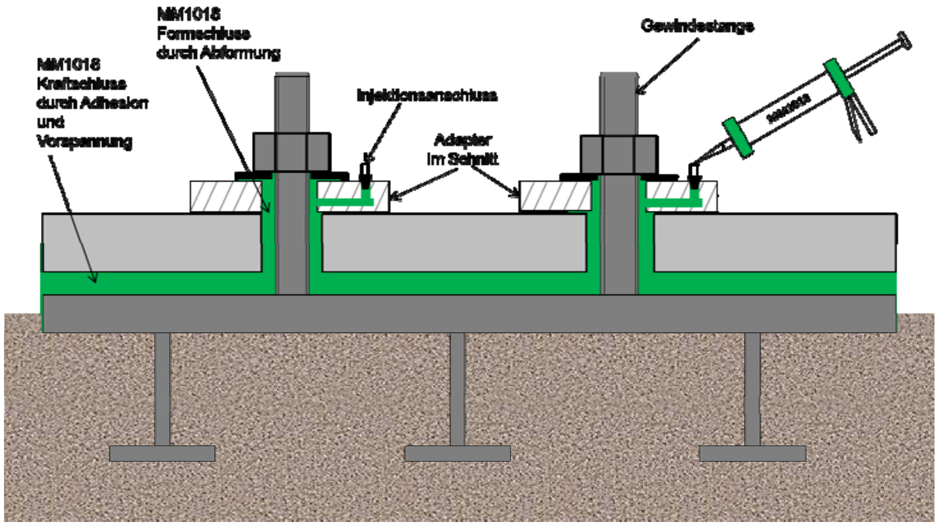
BULLE building

Dr. Deuring + Oehninger AG
Dipl. Bauingenieure ETH SIA USIC

Steel Support foundations

Steel Support foundations

Steel Support foundations



Steel Support foundations

Steel Flanges

Wynn Palace casion Macau, 2015
Gap compensation on steel construction of dragon towers

Steel Flanges

Steel Flanges

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MM1018 advantages at a glance

- 100% gap filling (force and form fit)
- No machining – It always matches!
- Quick application in field
- Corrosion protection for flange areas
- Weather proof, resistant to many oils, lubricant, Salt water, etc.
- Long time experience, more then 1.000 buildings arround the world
- Service and application through DIAMANT engineers
- Approved material data
- Saves time, money and nerves

DIAMANT
The Metalplastic Company

What

can we

Do

for you?

DIAMANT Coating Systems
Contact - Larry F Grimenstein
Phone : 937-704-4020
E-Mail: strongholdone@cs.com