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Evaluation of Structural Fillers for “Steel Grouting” in Steel Bridge Preventive Maintenance and Repairs

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Abstract:

In some instances, steel bridges can contain gaps between steel plates in bolted connections or between steel and concrete surfaces. In new bridges, these gaps may result from fabrication or assembly errors. In existing structures, the gaps often arise because of corrosion-related section loss. These gaps can also cause durability concerns because they are a place for water and salt to collect, leading to crevice corrosion. In concrete bridges, such gaps are commonly filled with cementitious grouts, but no widely accepted method exists for filling the gaps in steel bridges. Structural fillers, such as epoxies, offer a preventive maintenance solution for filling these gaps to alleviate future crevice corrosion concerns. However, despite the wide range of structural fillers used across various industries, information is limited on the selection and performance of structural fillers for steel bridge preventive maintenance applications.

This study investigated the performance of “steel grouting,” which is structural fillers for filling gaps in steel bridges, through laboratory testing and field evaluations. First, the research team developed a list of potential structural fillers and their key properties. Three fluid (injectable) and three putty structural fillers were selected for experimental testing of material and structural properties. Material tests of selected structural fillers included compressive strength testing at different curing temperatures and creep testing under sustained compressive loads at elevated curing temperatures. Results from these tests were used to narrow down the selection of structural fillers for structural component testing with slip-critical bolted connections. For these tests, fluid structural fillers were injected into a 1/8-inch thickness, and putty structural fillers were placed in a 1/2-inch thickness between steel plates. Compressive slip and tensile creep tests were conducted according to standard test procedures on specimens with both blast-cleaned and organic zinc faying surfaces. Lastly, field evaluations were conducted on previous Virginia Department of Transportation (VDOT) applications that used structural fillers for preventive maintenance, including bolted beam end repairs and bearing corrective actions, to evaluate their performances after multiple years of service.

The study concluded that structural fillers possess sufficient strength and stiffness to remain intact under compressive service loads when used for filling gaps, or steel grouting, in preventive maintenance of steel bridges. Because of their sufficient strength and stiffness, structural fillers can improve the constructability of bolted plate repairs by preventing deformation of the existing structure or repair plates during tensioning of bolted assemblies. Based on the structural component testing performed in this study, structural fillers cannot be considered incompressible, so pretensioned bolts with structural fillers within their grip length should not be considered slip-critical. Structural fillers can experience compressive creep when cured at high temperatures. This issue can be alleviated by casting and curing structural fillers within the manufacturer’s recommendations. In addition, field evaluations found that previous VDOT applications using structural fillers for preventive maintenance appeared to be performing well after multiple years of service. The study recommends that the Virginia Transportation Research Council develop guidance for using structural fillers to fill gaps to provide constructable and durable steel bridge preventive maintenance and repairs and implement this guidance into VDOT specifications.

Supplemental materials can be found at https://library.vdot.virginia.gov/vtrc/supplements.

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Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

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ABSTRACT

In some instances, steel bridges can contain gaps between steel plates in bolted connections or between steel and concrete surfaces. In new bridges, these gaps may result from fabrication or assembly errors. In existing structures, the gaps often arise because of corrosion-related section loss. These gaps can also cause durability concerns because they are a place for water and salt to collect, leading to crevice corrosion. In concrete bridges, such gaps are commonly filled with cementitious grouts, but no widely accepted method exists for filling the gaps in steel bridges. Structural fillers, such as epoxies, offer a preventive maintenance solution for filling these gaps to alleviate future crevice corrosion concerns. However, despite the wide range of structural fillers used across various industries, information is limited on the selection and performance of structural fillers for steel bridge preventive maintenance applications.

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INTRODUCTION

In some instances, steel bridges can contain gaps in between different components. For existing bridges, these gaps can be the result of bolting a new steel repair plate to an existing deteriorated beam, such as a bolted repair on a beam end that has section loss due to corrosion. For new bridges, these gaps can be the result of an uneven concrete abutment, creating a gap between the top of the concrete abutment and the bottom of the steel masonry plate. Regardless of whether on new or existing bridges, these gaps can present durability concerns. These gaps can present an opportunity for water and salt to collect, eventually leading to accelerated crevice corrosion.

When such gaps occur in concrete bridges, cementitious grouts are commonly used to fill them. Cementitious grouts are ideal for filling these gaps on concrete bridges because they have similar material properties to concrete, high compressive strength, low shrinkage, and are relatively inexpensive and simple to use. However, a widely accepted counterpart preventive maintenance or repair technique does not exist for steel bridges. One possible preventive maintenance technique investigated by the American Institute of Steel Construction (2019) is the use of structural fillers to fill these gaps.

For the purposes of this report, structural fillers are defined as a material that can be injected into a small void or troweled onto a surface to be used for filling gaps on steel bridges or "steel grouting" for preventive maintenance—hence, the "filler" portion of the name. Structural fillers must also have sufficient material properties to withstand the loads applied to them while in service on a bridge—hence, the "structural" portion of the name. These structural fillers can take the form of many different product types, including epoxy adhesives, epoxy grouts, polymers, epoxy putties, and so on. However, in general, many structural fillers are made up of a two-part epoxy that can be mixed into a fluid or putty form and then injected into a gap or troweled onto a surface, respectively. Some can even be filled with steel or other metal particles to provide different material properties. Once cured, these structural fillers should provide high strength and low shrinkage (Provines, 2021).

The Virginia Department of Transportation (VDOT) has been using structural fillers for steel grouting in preventive maintenance for filling gaps in steel bridges to prevent future corrosion. These structural fillers have generally been used in two types of applications: (1) restoring thickness on a corroded beam end before installing a bolted plate repair and (2) filling a gap between the top of an uneven concrete abutment and the bottom of a steel masonry plate at a bearing. Both application types will be briefly introduced.

Error! Reference source not found. shows an example of how VDOT's Richmond District has used structural fillers for preventive maintenance as part of bolted bent plate repairs on corroded beam ends. In these applications, the web of the existing beam had experienced corrosion or section loss, necessitating a repair. Bent plates were used to eliminate the crevice that would be present at the web-to-flange interface if separate plates for the web and flange had been used. Structural fillers were included in these repairs for two reasons. The first reason was to prevent the intrusion of water or deicing salts into spaces between the repair plates and existing beam web, especially in areas where the beam web is corroded. The second reason was for constructability purposes during the bolted repair installation. Prior to including structural fillers in these repairs, the concern was that gaps between the repair plates and the existing corroded beam web could cause the repair plates to be deformed or bent during the bolt tensioning process. Therefore, a putty-type structural filler was included in these repairs.

The general process by which these beam end repairs are installed is as follows. First, one of the bent plates for the repair is predrilled. The other bent plate and flat plate are field drilled after installation. The existing steel beam end is blast cleaned, and the existing steel beam and all repair plates are coated. Then, the structural filler is mixed and troweled onto the repair plates, and the repair plates are installed onto the existing beam using snug-tight galvanized bolted assemblies. Next, bolts without structural filler within their grip length are fully tensioned, and bolts with structural filler within their grip length are left as snug-tight. After the structural filler is cured, the bolts with structural filler within their grip length are fully tensioned. A fillet weld is used to seal the gap along the bent plate and the bottom flange above the bearing where bolting is not possible. Finally, the perimeter and ends of the bent plate are sealed with a silicone sealant.

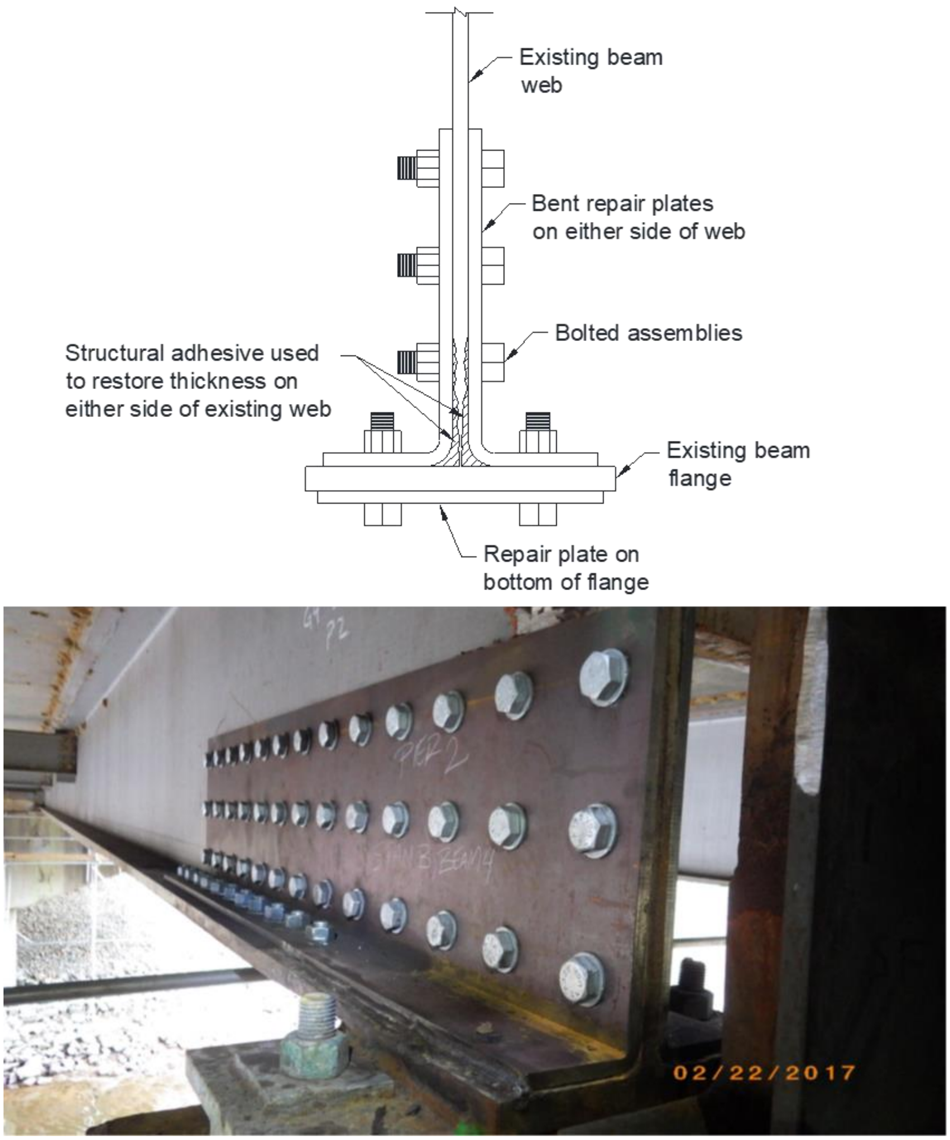


Figure 1. Steel Grouting Example with Structural Filler Used to Restore Thickness on Existing Beam with Bolted Repair Plates

VDOT's Northern Virginia District has also used structural fillers for steel bridge preventive maintenance to fill gaps between the top of an uneven concrete abutment and the bottom of a steel masonry plate at a bearing. These gaps were likely due to a construction error when erecting the concrete abutments. These gaps, between the concrete abutments and steel masonry plate, are typically less than 1/2 inch and cannot be filled with cementitious grout because the maximum aggregate size in cementitious grout is typically larger than the gap height, so the cementitious grout would not be able to flow into the void. Instead, structural fillers have been injected into these gaps to fill them to prevent water and deicing salt from entering them and causing future crevice corrosion. These gaps have typically been filled by first constructing formwork around the gap, leaving some inlet and outlet openings. Then, fluid structural fillers are injected into the inlet openings until the fillers flow out of the outlet openings. Different types of structural fillers can be used, depending on the thickness of the gaps. Figure 2 shows before and after photos of this application.

Figure 2. Gaps between Steel Masonry Plate and Concrete Abutment Seat Before (left) and After (right) Structural Fillers Were Used for Preventive Maintenance

Structural fillers can potentially also be used as repair strategies in bolted splices that are designed as slip-critical connections. Gaps between plates can result from fabrication errors or fit-up challenges. **Error! Reference source not found.**3 shows an example diagram of a potential top flange bolted splice connection. In Figure 3, the girder on the right side is a slight distance upward relative to the girder on the left side, creating a gap between the splice plate and both girder flanges. Aside from potential crevice corrosion concerns, these gaps mean that some of the bolts in the connection will not function as slip-critical because the plates in the connection are not in contact with one another. This type of problem has potential to be solved by injecting a structural filler into the gaps but only if structural fillers behave as "incompressible," such that they can transfer frictional loads from the girder flanges to the splice plate. Currently, it is unknown if structural fillers behave as incompressible.

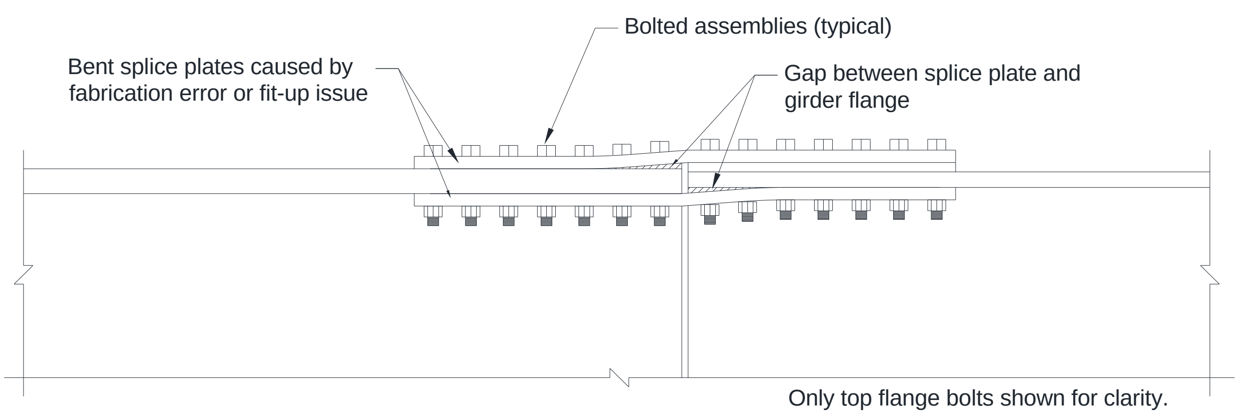


Figure 3. Diagram of Potential Bolted Splice Gap with Gaps between Splice Plate and Flange

Although VDOT has had success using structural fillers, some questions remain about their use for steel bridge preventive maintenance. First, structural fillers are not addressed in the VDOT Road and Bridge Specifications, so no VDOT-wide policy exists about their use (VDOT, 2020). Second, it is not fully understood if structural fillers possess the required strength and stiffness properties to remain intact under service loads on a bridge. A related uncertainty is whether structural fillers have the required strength and stiffness to prevent deformation of the repair plates during bolt tensioning when used on bolted beam end repairs. Third, it is unknown if structural fillers can be considered incompressible to function as part of a slip-critical connection if the structural fillers are used to restore thickness in bolted splice application. Lastly, although structural fillers are reported to have been functioning well, unknowns still exist about the long-term performance of structural fillers in bridge environments.

PURPOSE AND SCOPE

The purpose of this project was to evaluate a selected number of structural fillers for use as steel grouting in steel bridge preventive maintenance. This evaluation included three aspects. The first aspect was to evaluate whether structural fillers possess sufficient strength and stiffness to withstand in-service loads and to prevent deformation of repair plates during bolt tensioning on bolted beam end repairs. The second aspect was to evaluate whether bolted connections with structural fillers within the pretensioned bolt grip length can be considered slip-critical. The third aspect was to evaluate the durability of structural fillers used for VDOT bridge maintenance projects after numerous years of service.

Within this scope, the research team conducted both laboratory testing and field evaluations. Laboratory testing included both material testing and structural testing on selected structural fillers. Material testing was used to evaluate the compressive strength of structural fillers, and structural testing was used to evaluate whether structural fillers can be considered incompressible to use on slip-critical bolted connections. In addition, field evaluations included site visits to previous VDOT preventive maintenance actions using structural fillers to evaluate their long-term durability.

METHODS

Overview

This research project consists of four tasks to achieve the main research objective. The research tasks are listed as follows and described in detail in the next four subsections:

1. Detailed literature review and structural filler selection.
2. Material testing on structural fillers.
3. Structural component testing on connections with structural fillers.
4. Field evaluation of previous VDOT preventive maintenance using structural fillers.

Literature Review and Structural Filler Selection

The research team conducted a literature review on the use of structural fillers in infrastructure applications and for filling gaps as a repair strategy in steel bridges. In addition to the literature review, the research team investigated many types of structural fillers for their potential use. This investigation included interviewing structural filler manufacturers to determine which products they recommended for VDOT applications. During this process, researchers compiled the following information on all the structural fillers: compressive strength, elastic modulus, tensile strength, flexural strength, shear strength, creep, viscosity, minimum and maximum intended thickness, and intended application. This information was used to select six structural fillers for the proceeding tasks.

Material Testing on Structural Fillers

The research team conducted material tests to determine the bulk material properties of the structural fillers selected for this study. The following tests were considered in the material testing:

- Compression testing to determine the maximum compressive strength of structural fillers under different curing temperatures.
- Creep testing to determine the compressibility of structural fillers under sustained compressive load and subject to high curing temperature.

Compressive Strength Tests

The research team conducted compressive strength testing to evaluate the maximum compressive strength of structural fillers. This property is critical because the applications in which structural fillers are used are subject to high compressive stresses. Compressive testing for rigid polymers, including structural fillers, follows the testing guidelines of ASTM D695 (ASTM International, 2015). The specimens were 0.5 × 0. 5× 1.0-inch rectangular prisms.

The process for preparing the specimens first included molding and curing the structural fillers in a silicon mold. The molds were primed with an epoxy-silicone release agent to ensure easy separation. Once the structural fillers were mixed adequately, as per the producers' technical sheet documents, they were applied to the mold cavities and placed in an environmental chamber to allow the epoxy to cure at the desired temperature and humidity. After the samples had cured for 6 days, they were removed and then cut to the desired size via a water jet. The samples were then placed back into their environmental chambers for an additional 24 hours before starting compression testing. A 7-day total curing time was selected for consistency among all the structural fillers and for simplicity of testing. The structural filler technical datasheets all had differing recommended curing times, including some with expected strength values for different curing times.

To evaluate the effects of temperature changes on the compressive strength of structural fillers, the research team considered three different curing temperatures: hot, room, and cold temperatures. Researchers selected 110°F for the hot temperature to represent a common hot temperature in the state of Virginia (90°F), plus an additional 20°F to account for the effects of solar radiation. Room temperature, approximately 73°F, was chosen as a convenient baseline for testing. For cold conditions, a temperature of 40°F was selected for the tests as a lower temperature limit in which structural fillers would be practically used for bridge projects. This limit was due to both the structural filler material limitations and the associated difficulties with conducting these types of repairs in cold weather. Note that the structural filler technical datasheets all had recommended curing temperature ranges to produce optimum properties. In many cases, the hot and cold temperatures were outside of these recommended curing temperature ranges. However, because bridges in Virginia are subject to these temperatures, and therefore, the structural fillers could be cured in these environments, these curing temperatures were considered for evaluating the structural fillers' compressive strength. Table 1 summarizes the test matrix for the compressive tests.

Table 1. Test Matrix for Compressive Tests

Variable	No. Tested	Details
Adhesive Type	6	Determined based on Task 1 results
Curing Temperature	3	Cold: 40°F Room: 73°F Hot: 110°F
Replicates	3	For repeatability

The research team used a servo-hydraulic-controlled uniaxial test frame with a 22-kip load capacity to conduct the tests. Figure 4 shows the test setup. A laser extensometer, which measured the displacement between reflective tape attached to the top and bottom of the samples, was used to collect displacement data. The built-in load cell of the test frame recorded the load data during the tests. The tests were conducted in a displacement-controlled manner, with a loading rate of 0.05 inch/minute. Each test continued until the samples failed, with real-time displacement and force data recorded.

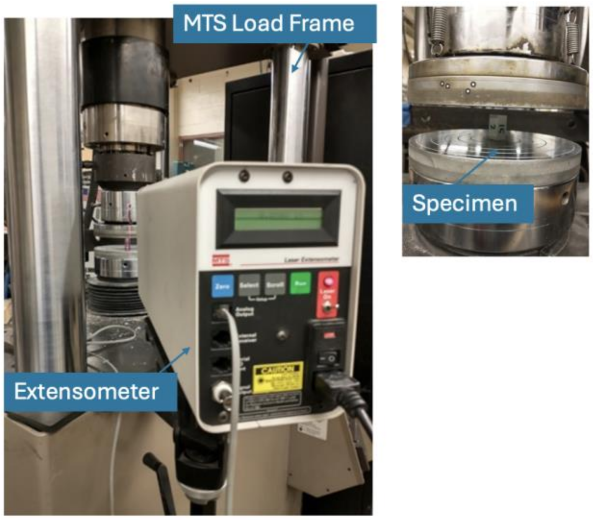


Figure 2. Photos of Compressive Strength Test Setup. MTS = MTS Systems (company).

Compressive Creep Testing

The research team also conducted creep testing of the selected structural fillers. Creep, also known as cold flow, refers to a time-dependent dimensional change caused by sustained loading. The structural fillers in both bolted connection repairs and bearing preventive maintenance are subjected to significant, prolonged compressive loads. If the structural filler were to creep under these conditions, it would lose its load-bearing capacity. In the case of bolted connection repairs, this loss could lead to deformation of the repair plates during bolt tensioning.

Therefore, creep testing is important to assess the performance of the selected structural fillers and determine their suitability for steel bridge preventive maintenance.

The creep testing was performed according to ASTM C1181 guidelines (ASTM International, 2017). The adhesive samples were cylindrical, with an outer diameter of 4 inches and a height of 2 inches. A 1-inch-thick square steel loading plate, measuring 4-1/2 inches on each side, was placed on both the top and bottom of the specimen to facilitate loading. Both the steel loading plates and the epoxy specimen had a 1-1/8-inch-diameter through-hole along their centerlines to enable post-tensioning after compressive loading. In addition, the top steel loading plate featured four 1/4-inch-diameter holes for measuring the height of the epoxy specimen with a depth micrometer. Figure 3 shows a diagram of the ASTM C1181 creep test specimen.

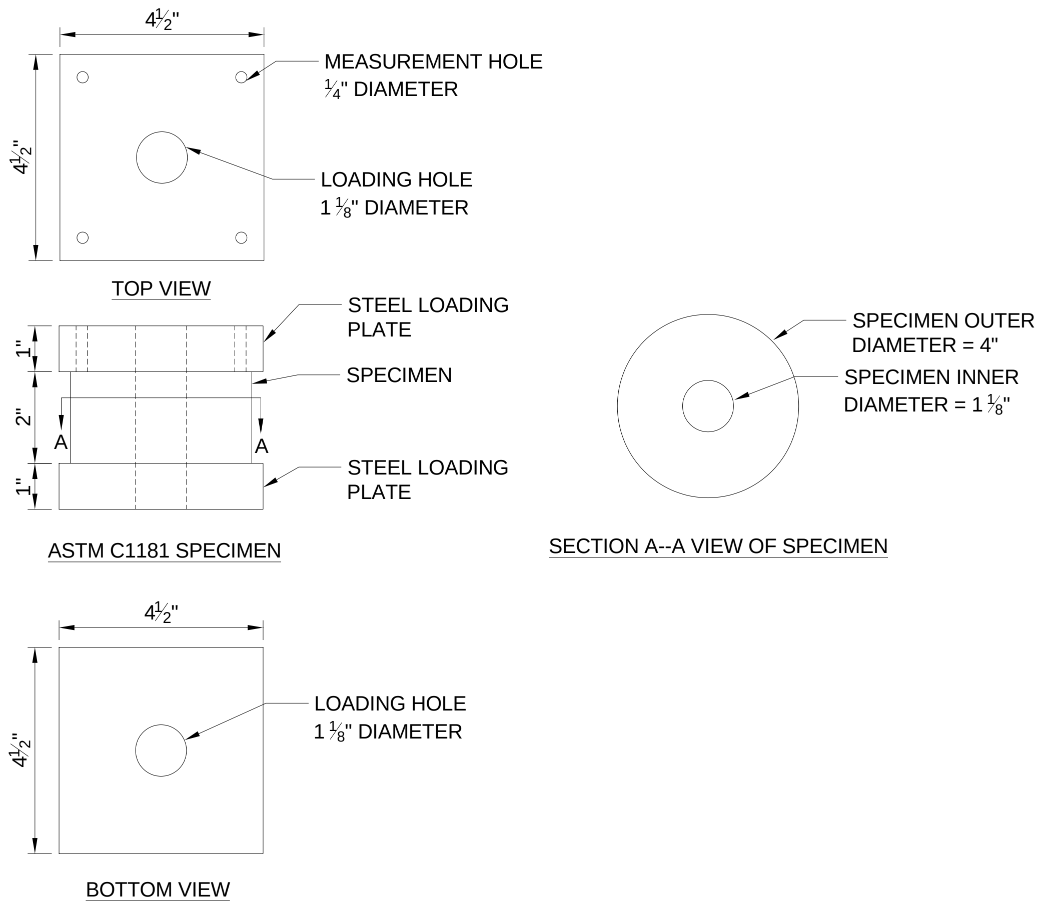


Figure 3. Diagram of Creep Test Specimens Based on ASTM C1181 (ASTM International, 2017)

To prepare the specimens, the research team made a custom mold using 1-inch-thick steel plates stacked on top of one another and fastened together using four nuts and bolts on each corner (Figure 4). The structural fillers were mixed and then placed into the mold. The fluid structural fillers were poured through a hole on top of the mold, and the putty structural fillers were troweled into the mold.

Figure 4. Photos of Compression Creep Mold

Following ASTM guidelines, the mold containing the curing structural filler was left under laboratory conditions for at least 24 hours before being disassembled (ASTM International, 2017). The hardened structural filler was then placed in an environmental chamber for 7 days to complete the curing process. The environmental chamber was set to 110°F with 50% humidity. The 110°F temperature was selected because it was expected to produce the worst case creep performance for the structural fillers. On the sixth day of curing, the specimen was removed, and a center hole was cut through the structural filler sample using a water jet. After cutting, the specimen was returned to the environmental chamber to complete the final 24 hours of curing.

Once cured, the specimen was measured and installed in its compression creep test fixture (Figure 5). The test fixture consisted of a 1-inch-diameter threaded rod running through the center of the specimen and steel loading plates. The threaded rod had four spring washers and three hardened flat washers with a nut on one side of each steel loading plate. The spring washers had a spring rate of 153,000 pounds/inch. The test fixture was then placed on top of steel plates in a servo-hydraulic-controlled test frame with a 22-kip loading capacity.

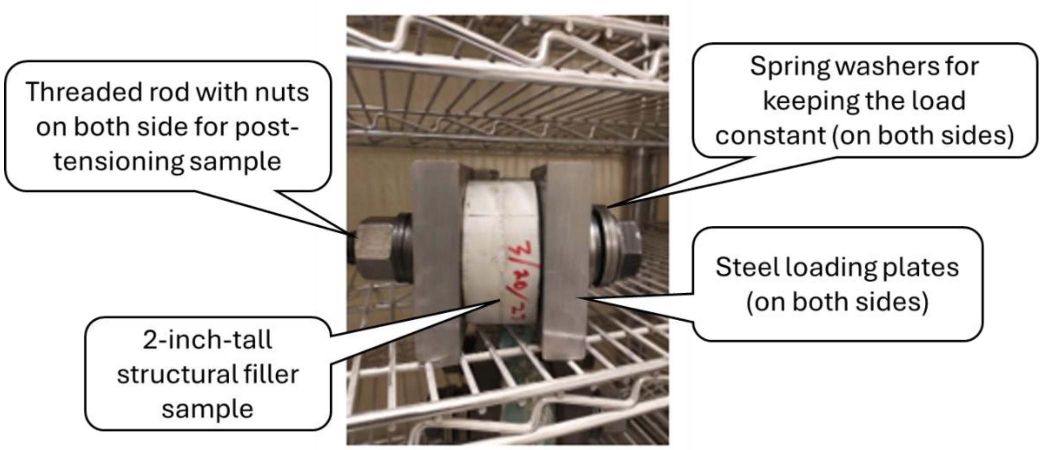


Figure 5. Photo of Creep Specimen Assembled in Compressive Creep Test Fixture

The load was applied to the specimen through the threaded rod using the test frame. The applied load, *P*, was calculated using Equation 1.

$$P = S\left(\frac{\pi D^2}{4} - A\right) \quad \text{(Equation 1)}$$

Where:
S = desired target stress, which was set to 400 psi based on input from structural filler manufacturers.
D = diameter of the sample.
A = area of the formed bolt hole.

The target stress was determined through input from structural filler manufacturers because ASTM C1181 does not provide any guidance on the stress level during the compressive creep testing (ASTM International, 2017).

The research team loaded the test fixture slowly until reaching the target force of 4.6 ± 0.05 kips. Once the target load was achieved, the nut on the bottom steel loading plate was hand-tightened to a snug-tight position, ensuring the threaded rod maintained the load on the structural filler specimen. After tightening the nut, the load from the test frame was removed, and the test fixture was removed from the test frame.

Following the application of applied creep load, the specimen depth was measured using a depth micrometer at all four corners between the top and bottom steel loading plates, and the average sample depth was recorded. The test fixture was then placed in an environmental chamber set to 110°F with 50% humidity for various time periods. The ASTM C1181 guidelines recommend measuring and loading the specimen in cycles, as Table 2 outlines (ASTM International, 2017). Over time, researchers expected the center threaded rod in the test fixture to gradually relax and lose stress as the structural filler experienced strain because of creep. Therefore, the researchers measured the specimen depth, reloaded the test fixture, and remeasured the specimen depth. The researchers performed this process at progressively longer intervals because creep was expected to be most substantial near the beginning of the test period. ASTM C1181 further specifies that the test fixtures be placed in laboratory conditions for 24 hours prior to any measurements or loading, regardless of prior environmental conditioning (ASTM International, 2017). This process was repeated for 672 ± 12 hours for each set of specimens. After this time, the compression creep test was concluded.

Table 2. Compression Creep Exposure Periods

Cycle Number	Time for Environmental Exposure for Cycle (hours)	Total Environmental Exposure Time (hours)	Time for Specimen Relaxation at Lab Conditions Before Test (hours)
1	24	24	24
2	24	48	24
3	72	120	24
4	48	168	24
5	168	336	24
6	336	672	24

Structural Component Testing on Connections with Structural Fillers

The purpose of the structural testing was to evaluate the structural fillers' performance for use in structural connections. This testing on structural fillers included two types of tests, as follows:

- Short-term compressive slip tests to determine the slip performance of structural fillers in bolted connections and their slip coefficient if used in slip-critical bolted connections
- Tension creep tests to evaluate the slip performance of the structural fillers in a slip-critical connection subject to sustained tensile loading

Each of these tests is further described in the following two sections.

Short-Term Compression Slip Tests

The research team performed short-term compression slip tests to determine the slip coefficient of structural fillers in slip-critical bolted connections. These tests followed the basic procedure outlined in Appendix A of the Research Council on Structural Connections (RCSC) specifications (RCSC, 2020), with the modification of applying a layer of structural filler between the faying surfaces of the bolted connection.

Four different structural fillers were tested on two types of steel surfaces. The steel plates in all specimens were made of ASTM A588 steel (i.e. "weathering steel"), with two distinct faying surface conditions, as defined in the *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2020). One faying surface type was a Class B, blast-cleaned surface with a design slip coefficient value of 0.50 ($k_s = 0.50$). The other faying surface type was a Class A organic zinc-coated surface with a design slip coefficient value of 0.30 ($k_s = 0.30$). Both faying surface types were considered in this testing because VDOT districts have indicated that either type could be used when conducting a bolted repair on an in-service steel bridge.

The compression slip specimens consisted of three steel plates, each measuring 4 × 4 inches with a thickness of 5/8 inch. A 1-inch-diameter hole was drilled in the center, positioned 1-1/2 inches from one end. The structural filler thickness varied depending on the type of structural filler used. Fluid structural fillers had a 1/8-inch thickness, and putty structural fillers had a 1/2-inch thickness, both reflecting bridge preventive maintenance application conditions. The entire specimen was drilled to allow fasteners to pass through, with an overhang designed to transfer the applied load from one path to two paths in double-lap shear. Figure 6 illustrates these test specimens.

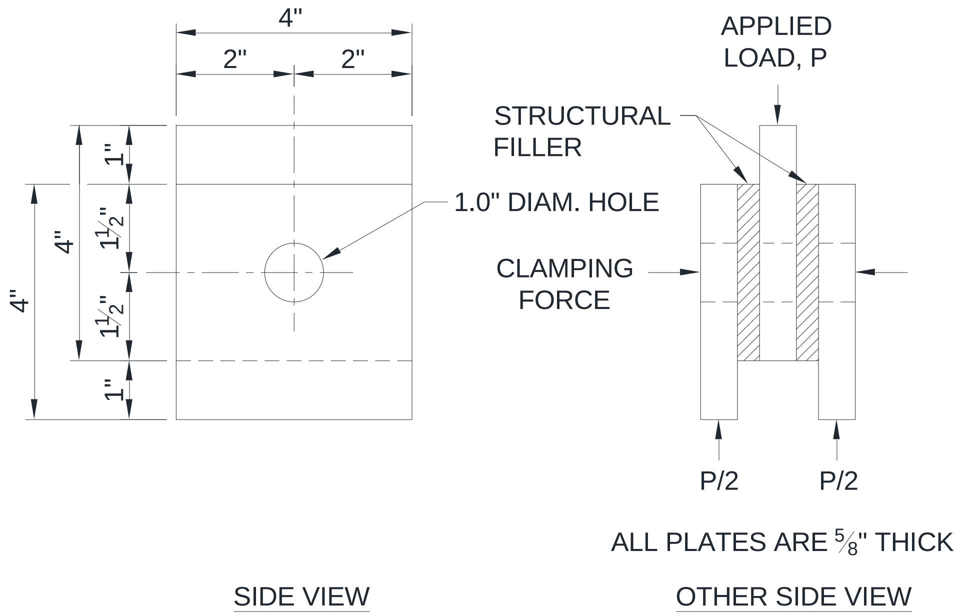


Figure 6. Diagram of Short-Term Compression Slip Test Specimen

Structural fillers were mixed, poured into empty caulking tubes, and then injected into the gaps in the plates made by the molds. The research team then cured the specimens for 7 days under laboratory conditions before removing the mold and preparing the specimens for testing. The samples were painted with a black-and-white speckled pattern used in conjunction with a digital image correlation system to measure specimen displacement (Figure 7). The clamping force on the specimens were applied by a 7/8-inch-diameter, 3-foot-long threaded rod passing through a center hole hydraulic jack with a 100-kip external load cell (Figure 7). The vertical load was applied in a servo-hydraulic-controlled test frame with a 220-kip loading capacity. The load cell in the test frame was used to record the applied load during testing.

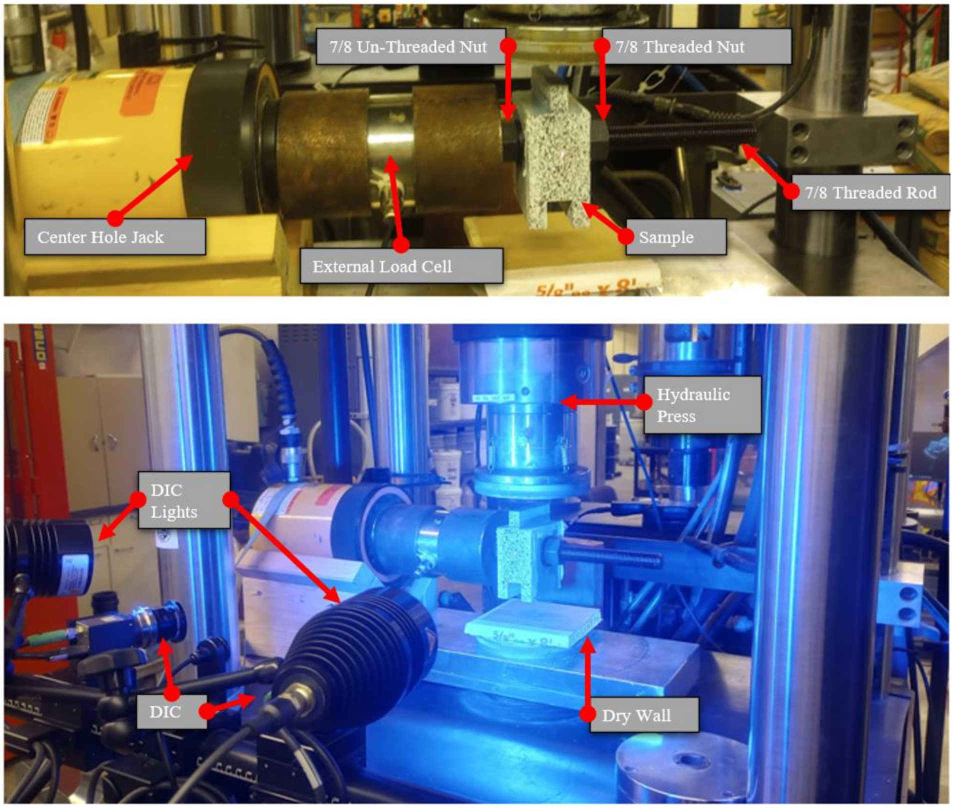


Figure 7. Photos of Test Setup for Compression Slip Tests. DIC = digital image correlation system.

The research team assembled the specimen and placed it into the test frame, then loaded the center hole jack to 5 kips to apply a small clamping force to the specimen. The specimen was then seated on a piece of 5/8-inch-thick drywall to account for any minor imperfections in the parallelism of the bottom of the two outer plates of the specimen. The digital image correlation system was then calibrated before applying any vertical compressive loading. Next, a vertical load of approximately 25 pounds was applied to the specimen, and the center hole jack was loaded to the desired clamping force of 50 ± 0.5 kips that was maintained for the remainder of the test. Vertical load was applied at a rate of 0.003 inch/minute. According to the RCSC specifications, the tests are concluded when the relative slip between the one inner and two outer plates exceeds 0.04 inch (RCSC, 2020). The RCSC specifications also provide examples for analyzing the compressive test data to determine slip load (Figure 8).

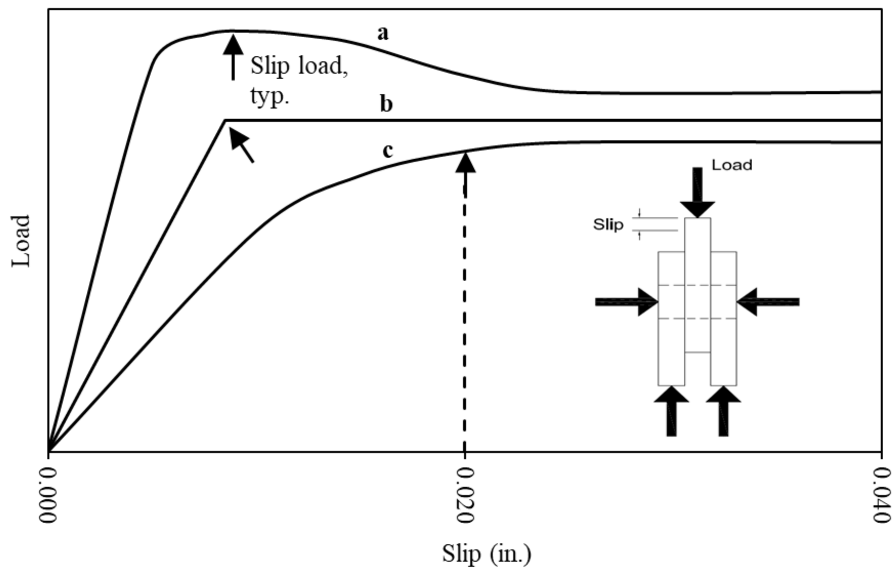


Figure 8. Diagram Defining of Slip Loading as Indicated in Research Council on Structural Connections (2020). Typ = typical.

The research team then calculated the slip coefficient using slip load and clamping force with the following equation, as provided in the RCSC specifications (RCSC, 2020):

$$k_s = \frac{\text{Slip Load}}{2 \text{ x Clamping Force}} \quad \text{(Equation 2)}$$

Long-Term Tension Creep Tests

Tension creep tests were used to evaluate the slip performance of the structural fillers in a slip-critical connection subject to sustained vertical tensile loading. The results of these tests provide insights on whether the compressibility of structural fillers causes detrimental slip in a slip-critical connection. Similar to the short-term compression slip tests, the RCSC specifications provide guidance for conducting the tension creep tests (RCSC, 2020). The tension creep tests used in this project followed those specifications except that a structural filler was applied in between the faying surfaces of the bolted connections.

Figure 9 shows a diagram of the tension creep test specimens. Each specimen consists of three 4 x 7 x 5/8-inch-thick weathering steel plates with two 1-inch-diameter holes drilled 1-1/2 inches from either end. Similar to the compression slip tests, two different faying surface types were tested: blast-cleaned and Class A organic zinc-coated surfaces. The specimens had a layer of cured structural filler between the steel plates: 1/8-inch-thick for fluid structural fillers and 1/2-inch-thick for putty structural fillers. The structural fillers were cured for 7 days before the start of creep testing.

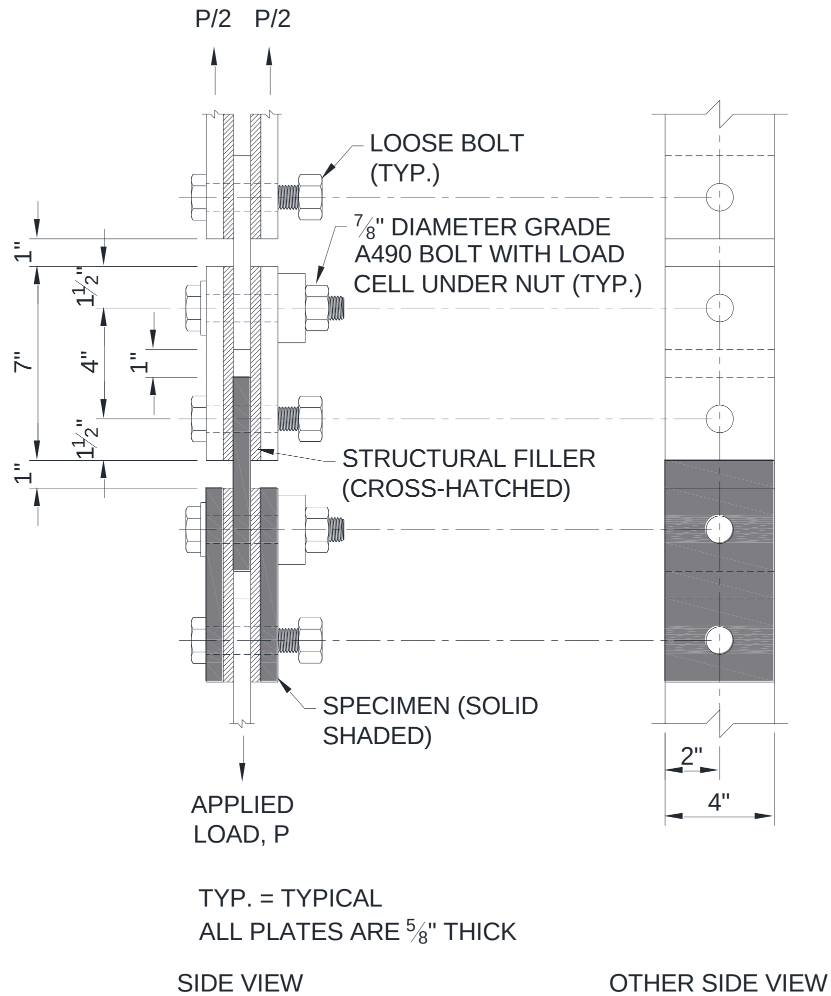


Figure 9. Diagram of Tension Creep Test Specimens. Typ = typical.

As Figure 9 shows, each specimen used a 7/8-inch-diameter ASTM F3125 Grade A490 bolt to connect the one inner and two outer plates together with layers of structural filler in between (ASTM International, 2022). The researchers placed a 100-kip load cell on this Grade A490 bolt to measure the clamping force in the bolt throughout testing. This process was done to determine if the structural filler experienced any creep or deformation that caused the initial clamping force in the bolt to relax. Figure 12 features photographs of the tension creep specimens before and after the structural filler casting. The Grade 490 bolt in each specimen was tightened to a clamping force of 50 ± 0.5 kip using an impact wrench and a self-reacting frame.

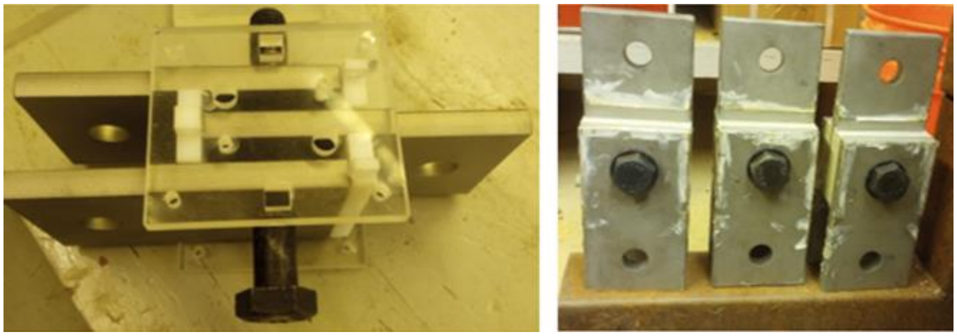


Figure 10. Photos of Tension Creep Specimens (left) Before and (right) After Casting the Structural Filler

Three specimens were arranged in an end-to-end “daisy chain” and placed into the test frames for applying the vertical load, all according to the RCSC (2020) specifications. The specimens were connected with loose 7/8-inch-diameter Grade A490 bolts to ensure an in-line load path. Figure 11 shows the final daisy chain of three specimens attached to the load frame. One displacement dial gauge was attached with a magnet to each side of each specimen (two dial gauges per specimen) to measure the relative slip between the one inner and two outer plates of the specimen.

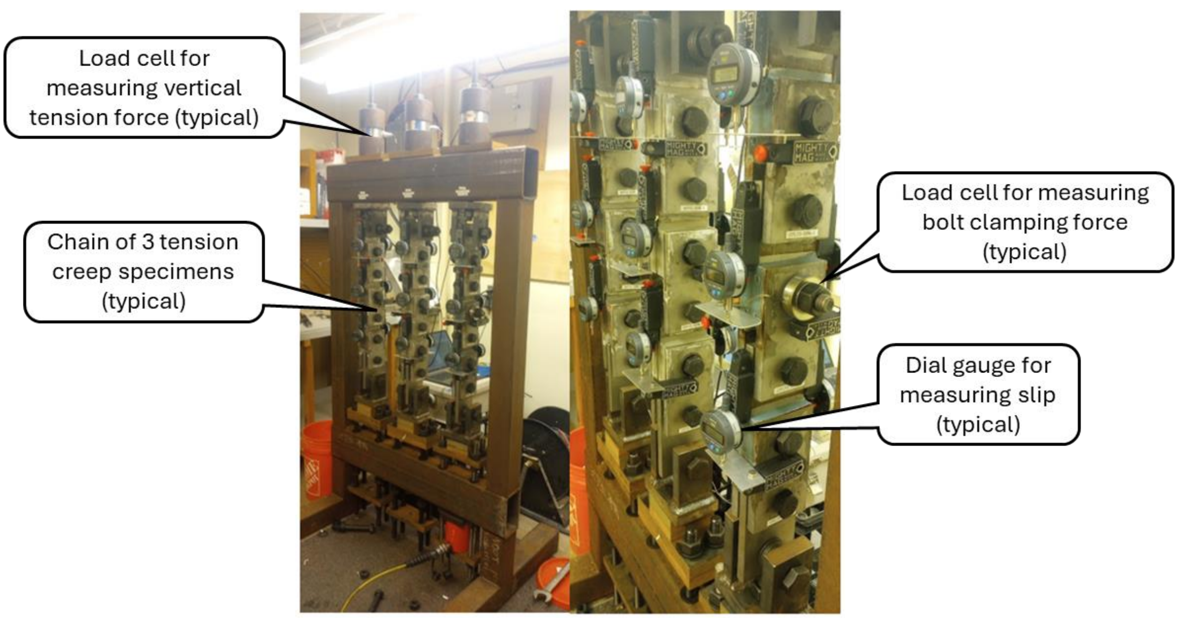


Figure 11. Photo of Load Frames, Instrumentation, and Tension Creep Specimens Arranged in Three Chains of Three Specimens Each

The vertical tensile load, R, applied to the specimens was calculated using Equation 3:

$$R=\frac{2\mu_t T_t}{1.5} \qquad \text{(Equation 3)}$$

Where:

μ_t = slip coefficient for the slip coefficient category under consideration (μ_t = 0.50 for blast-cleaned surfaces; μ_t = 0.30 for Class A organic zinc coated surfaces).

T_t = average clamping force for all three specimens within a chain.

Researchers used a hydraulic jack to apply the vertical load to each chain of specimens and then hand-tightened a set of threaded rods to maintain the load, similar to post-tensioning. The vertical tensile load was measured at the top of the frame using a 100-kip capacity load cell positioned between the chain connection and the frame. The vertical tensile load was applied approximately 30 minutes after the clamping force was applied in each specimen, and this load was maintained within 1% of its initial value throughout the testing. During the test, clamping force values from the load cells on the Grade A490 bolts were recorded every 30 minutes, and slip readings from the dial gauges were manually recorded daily. Each test ran for 1,000 hours before being concluded.

Field Evaluation of Previous VDOT Preventive Maintenance Using Structural Fillers

VDOT has already used structural fillers for preventive maintenance on bearings and in bolted connection repairs. Some of this preventive maintenance was constructed in VDOT's Richmond and Northern Virginia Districts. Because some of this preventive maintenance has been in place for multiple years, the research team selected several sites to conduct field visits and assess how the structural fillers were performing in service. The assessments focused on visual examination. The research team worked with the two VDOT districts to coordinate these field assessments.

RESULTS

Literature Review and Selection of Structural Fillers

In this section, the review of the literature on the use of structural fillers in steel structures is first provided. Then, the initial screening and selection of structural fillers for experimental testing are discussed.

Literature Review

Epoxies have been the most widely used and researched structural fillers for steel construction applications. Available as both single-component and two-component systems, epoxies offer flexibility in application, depending on the specific requirements of the project. Although most epoxies cure effectively at ambient temperatures, elevated temperature curing can be employed to enhance the structural filler's performance, particularly in environments requiring rapid installation or higher thermal resistance. This curing can be achieved using various methods, including heat blankets, ovens, or heat guns, depending on the scale and location of the application. For two-component epoxies, the resin and curing agent must be combined in the correct proportions to ensure optimal mechanical properties and durability. Deviations from this ratio can lead to incomplete curing or weakened structural filler properties. In addition, the pot life—that is, the time window in which the mixed structural filler remains usable—varies depending on the formulation and environmental conditions, requiring careful management during large-scale or time-sensitive projects. Epoxy structural fillers are also highly resistant to environmental degradation, including exposure to moisture, ultraviolet radiation, and various chemicals, making them well suited for outdoor structural applications and harsh service conditions.

Most previous studies on epoxy structural fillers have primarily focused on structural adhesives and their tensile (Guo et al., 2022; Michels et al., 2016; Moussa et al., 2012), bonding (Campos et al., 2017; Firmo et al., 2019), or fatigue properties (Foletti et al., 2020), with less attention given to their compressive strength and compressive creep characteristics. As part of a larger research project, Rodrigues et al. (2017) evaluated the compressive strength of two epoxy structural fillers and found that the experimentally evaluated values are less than the values the manufacturer provided. Jahani et al. (2022) investigated the effects of curing, post-curing, and testing temperatures on the performance of a commonly used epoxy structural filler for concrete repair. The findings showed that when the structural filler is cured at varying temperatures but tested at room temperature, compressive strength increases moderately with higher curing temperatures. However, when the structural filler is cured at room temperature and tested under different environmental temperatures, compressive strength decreases as the testing temperature rises, and failure elongation increases. Although several studies have explored the tensile creep behavior of structural fillers (Costa and Barros, 2015; Cruz et al., 2021; Emara et al., 2017), no studies were found on the compressive creep response of structural fillers.

In bridges, bolted connections are designed as slip-critical when subjected to conditions such as stress reversals, vibrations, or heavy impact loads, on which any slip could compromise the performance or safety of the structure. The key feature of slip-critical connections is the reliance on friction between the connected surfaces to resist movement. This friction is generated by the clamping force applied by pretensioned bolts. Unlike bearing-type connections, which rely on the shear strength of the bolts, slip-critical connections transfer loads through frictional resistance at the faying surfaces. Therefore, a critical factor in the design of these connections is the condition of the faying surfaces, as it directly affects the slip resistance. The slip coefficient is a measure of the frictional resistance between the surfaces and depends on surface preparation and treatment, with different classifications provided in *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2020). Class A surfaces include clean mill scale surfaces and Class A coatings, such as organic zinc coatings, and are assigned a design slip coefficient value of 0.30. Class B surfaces include uncoated, blast-cleaned surfaces and are assigned a design slip coefficient value of 0.50.

The studies are very limited on the slip characteristics of steel surfaces with gap filling materials, such as structural fillers. Within the scope of a European project, the slip performance of a structural filler was evaluated through short-term creep tests (Makevičius et al., 2021). Two types of steel surfaces were considered, grit-blasted surfaces and grit-blasted and alkali-zinc-silicate-coated surfaces, with 2-mm-thick structural fillers between them. The study found the slip coefficient is 0.78 and 0.64 for the grit-blasted and zinc-coated surfaces, respectively.

Selection of Structural Fillers for Experimental Testing

The research team organized a list of epoxy structural fillers based on the previous studies on structural fillers and structural fillers used in past VDOT projects. The list also included selected structural fillers from the same manufacturers, which contained details on the mechanical and application properties for each structural filler. The properties documented by each structural filler manufacturer were not uniform, so some properties, like elastic modulus or creep behavior, were often not recorded in the documentation. Most technical documentation provided by the structural filler manufacturers followed ASTM standards for properties like ultimate compressive strength and tensile strength. Some products were manufactured by companies with overseas headquarters. These manufacturers typically reported that their properties followed International Standard Organization standards.

The desired usage of structural filler in this report is to fill gaps on steel bridges. Therefore, the structural filler should ideally behave similarly to steel, or as closely as possible. The primary loading condition for these bridge preventive maintenance applications is compression. The structural filler should have high-compression yield strength, high-compression ultimate strength, and a high elastic modulus. The high-compression yield strength reduces the likelihood of the structural filler undergoing plastic deformation. Ultimate strength is the peak stress that the structural filler can handle before it fails. This strength is critical for the integrity of the structural filler to prevent crevice corrosion and provide a load path. A high elastic modulus can minimize the compressibility of structural fillers and prevent the occurrence of slipping in slip-critical connections.

Other criteria the research team considered during the initial selection process included the viscosity and workability of the structural filler. A low-viscosity structural filler would behave like an oil or syrup, and a highly viscous structural filler would have a putty- or gel-like consistency. A structural filler with an oily consistency could be injected into small gaps between two surfaces. An example of this process is injecting an oil-type adhesive into a gap between a concrete abutment seat and steel bearing plate. In this case, formwork would be needed to maintain the outer perimeter limits of where the structural filler is being placed. A structural filler with a putty consistency could be troweled onto the surface of a vertical steel surface before another steel member is placed in contact with that first surface. An example of this procedure is placing a putty-type structural filler onto an existing corroded steel girder web before a bolted repair plate is placed into contact with it.

Workability is a measure of how long it takes before a structural filler becomes too rigid to place effectively. For two-part epoxies, workability, or working time, is typically defined starting from when the two parts are initially mixed. Workability is important for onsite effectiveness. Depending on the application, adequately mixing and placing structural fillers with short working times can be difficult. Often, the level of difficulty depends on the complexity of placing the structural filler.

Considering these criteria, the research team selected three fluid (injectable) and three putty structural fillers for experimental testing. Table 3 shows the mechanical properties of the selected structural fillers, and Table 4 lists their application properties. All properties listed in both tables were compiled based on the structural filler technical datasheets the manufacturers provided. The selected structural fillers were also given a structural filler identification (ID) to use throughout the remainder of the report for simplicity. The first letter in the structural filler ID refers to the specific structural filler manufacturer or product name. Adhesives with an ID ending in “FL” are fluid-type or injectable structural fillers, and structural fillers with an ID ending in

“P” are putty-type structural fillers. Notably, the MFL and MP structural fillers have the highest compressive strength for the fluid and putty categories, respectively. Also, only one structural filler, CFL, had creep properties reported on its technical datasheet. Note that most of the selected structural fillers have a simple volume mix ratio of one to one, except MFL and MP. For these structural fillers, the mixing ratio is provided as a weight ratio. The selected structural fillers have working times ranging from 10 to 90 minutes. Cost values at the time of purchase for the structural fillers are reported per gallon of structural filler.

Material Testing on Structural Fillers

Compressive Strength Results

The research team determined the compressive strengths of six different structural fillers under three different curing environments using data gathered during testing. Figure 14 presents the stress versus strain curves for the fluid structural fillers (HFL, CFL, and MFL), and Figure 15 plots the curves for the putty structural fillers (HP, CP, MP).

For HFL, the average compressive strength at room temperature after 7-day curing was 11.8 ksi, which is the same as the manufacturer’s specified strength of the structural filler. When this structural filler was cured at 40°F, compressive strength decreased 55%. When cured at 110°F, the structural filler was able to reach a compressive strength of 12.4 ksi, but this strength was reached after exhibiting significant compressive strains (about 0.4 inches/inch). At this curing temperature, the material yielded at very low stress levels (approximately 3–4 ksi) and then experienced strain hardening.

CFL had an average compressive strength of 12.8 ksi when cured at both room temperature and at 110°F. At high-temperature curing, CFL exhibited strain-hardening behavior and reached somewhat higher stress levels. In these cases, stress levels prior to significant yielding were reported as the compressive strength because significant deformations are not expected nor desired in these types of repair applications. At low curing temperature (40°F), the compressive strength was 8.3 ksi, reporting a 35% decrease. The manufacturer’s technical datasheets stated that the compressive strength of this structural filler was 19.0 ksi at room temperature. The structural filler reached only approximately 70% of this value during experimental testing. The strain at peak stress was 0.025, 0.038, and 0.047 inches/inch at 40°F, 73°F, and 110°F curing temperatures, respectively.

Table 3. Mechanical Properties of Selected Structural Fillers Reported by Manufacturers

Structural Filler ID	Structural Filler Product Name	Product Type	Compressive Strength (ksi)	Elastic Modulus[a] (ksi)	Creep (inch/inch)	Tensile Strength (ksi)	Flexural Strength (ksi)	Shear Strength (ksi)
HFL	Sikadur®-32 Hi-Mod	Epoxy adhesive	11.8	210	N/A	6.9	7 (14 days)	6.2 (14 days)
CFL	COPPS K-009	Epoxy grout	19.0[b]	N/A	1.62×10^{-3} (24 hours at 600 psi at 150°F)	4.5	9.2	N/A
MFL	Diamant MM1018 FL	Metal-filled polymer	23.4	1,450	N/A	N/A	N/A	N/A
HP	Sikadur-31 Hi-Mod Gel	Epoxy adhesive	12.3	560	N/A	3.3	6.1	4.6
CP	COPPS K-082	Epoxy adhesive	12.6	356	N/A	4.4	N/A	N/A
MP	Diamant MM1018 P	Metal-filled polymer	15.9	1,450	N/A	N/A	N/A	N/A

CFL = COPPS K-009; CP = COPPS K-082; HFL = Sikadur-32 Hi-Mod; HP = Sikadur-31 Hi-Mod Gel; N/A = not applicable; MFL = Diamant MM1018; MP = Diamant MM1018. [a]Under Compression; [b]After 30-day immersion in water at 72°F.

Table 4. Application Properties of Selected Structural Fillers Reported by Manufacturers

Structural Filler ID	Working Time[a] (min)	Mix Ratio (A:B)	Viscosity	Intended Thickness Range (inch)	Intended Applications	Cost at Purchase
HFL	30	1:1 by volume	Syrup	1.5 maximum lift	Machinery base-plate grout. Structural adhesive for concrete and metal.	$118/gallon
CFL	30	10:1 by volume	Syrup	0.5 maximum	High-performance grouting.	$72/gallon
MFL	89	21.3:1 by weight	Oil	0.4 maximum recommended	Gap compensation between bridge bearings and steel components.	$1,427/gallon
HP	60	1:1 by volume	Putty	N/A	Structural adhesive for concrete and metal. Grouting bolts and pins.	$78/gallon
CP	9	1:1 by volume	Putty	N/A	Structural anchorage bonding.	$67/gallon
MP	20	79:21 by weight	Putty	0.4 maximum recommended	Gap compensation between bridge bearings and steel components.	$1,879/gallon

CFL = COPPS K-009; CP = COPPS K-082; HFL = Sikadur-32 Hi-Mod; HP = Sikadur-31 Hi-Mod Gel; N/A = not applicable; MFL = Diamant MM1018; MP = Diamant MM1018. [a]At room temperature.

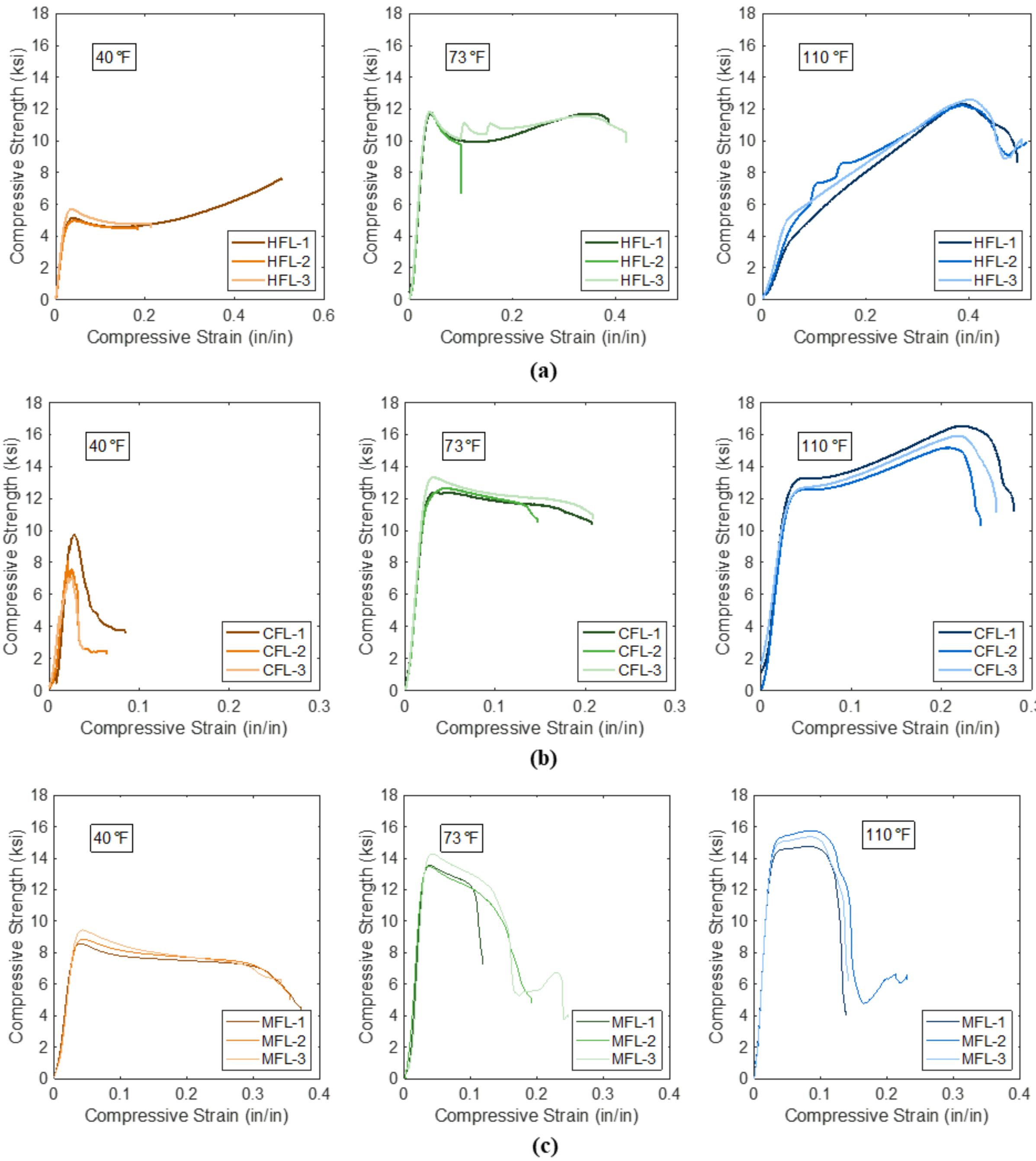


Figure 12. Compressive Stress-Strain Curves for Fluid Structural Fillers: (a) HFL; (b) CFL; (c) MFL. CFL = COPPS K-009; HFL = Sikadur-32 Hi-Mod; MFL = Diamant MM1018.

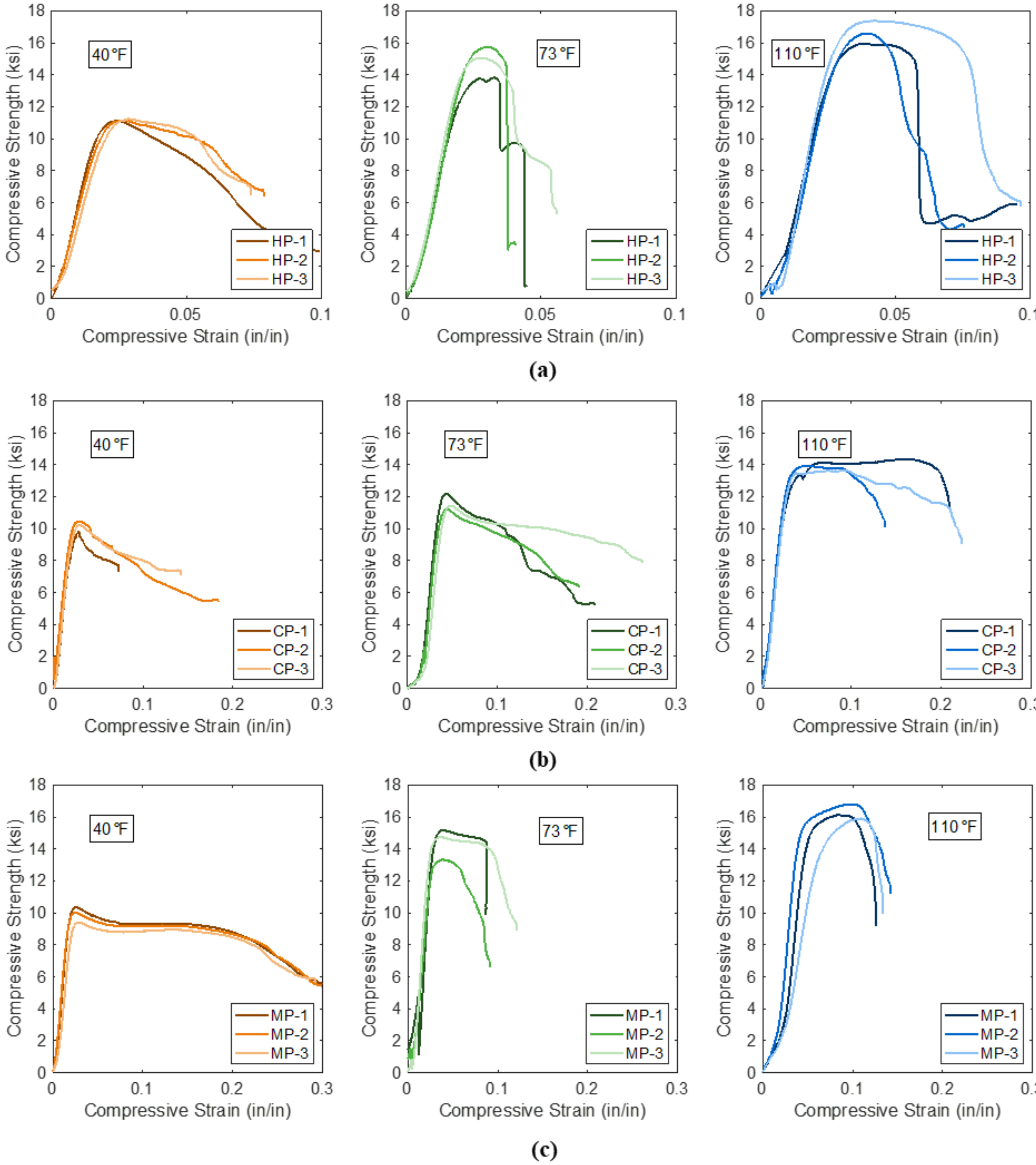


Figure 13. Compressive Stress-Strain Curves for Putty Structural Fillers: (a) HP; (b) CP; (c) MP. CP = COPPS K-082; HP = Sikadur-31 Hi-Mod Gel; MP = Diamant MM1018.

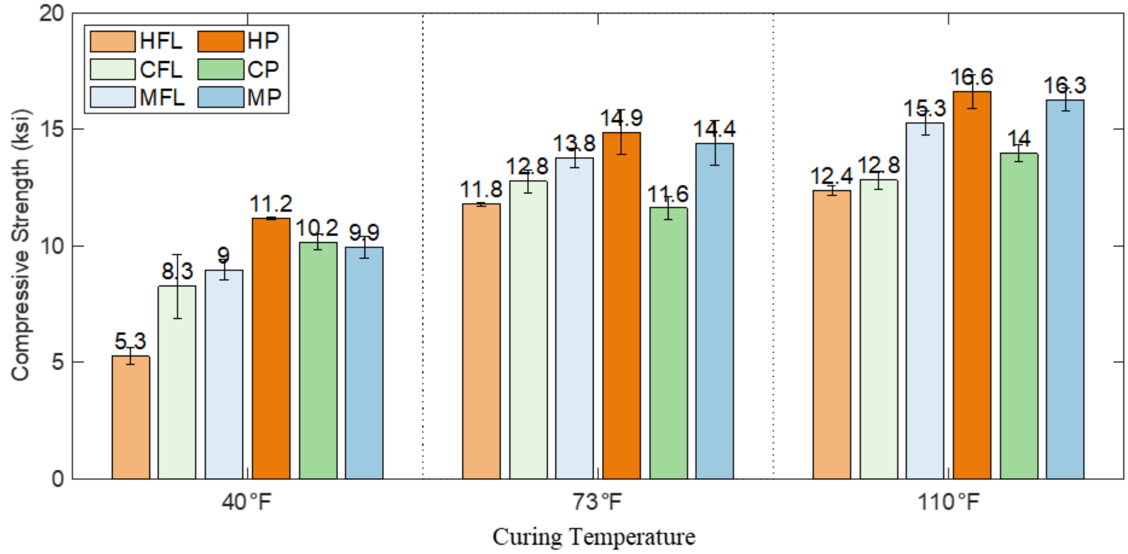
MFL exhibited an average compressive strength of 13.8 ksi at room temperature. This value decreased by 35% to 9.0 ksi at 40°F curing, and it increased by 10% to 15.3 ksi at 110°F curing. This structural filler displayed greater compressive strains at failure when cured at lower temperatures compared to the other structural fillers, which displayed greater strains when cured at higher temperatures. The strain at peak stress was about 0.04 for the three different curing temperatures. The compressive strength for MFL was specified as 23.4 ksi, which is much higher than the test results. This difference in performance could be partially due to the unconventional mix ratio of resin to hardener (21.3 to 1).

The stress versus strain curves of the putty structural fillers (HP, MP, and CP) exhibited similar characteristics to those curves of the fluid structural fillers. However, the decrease in compressive strength at low curing temperature compared with room curing temperature was lower: 25% for HP, 13% for MP, and 31% for CP. These fillers also exhibited an increase in compressive strength ranging from 11 to 17% when the structural filler was cured at high temperature. No strain-hardening behavior occurred at high curing temperatures for putty structural fillers.

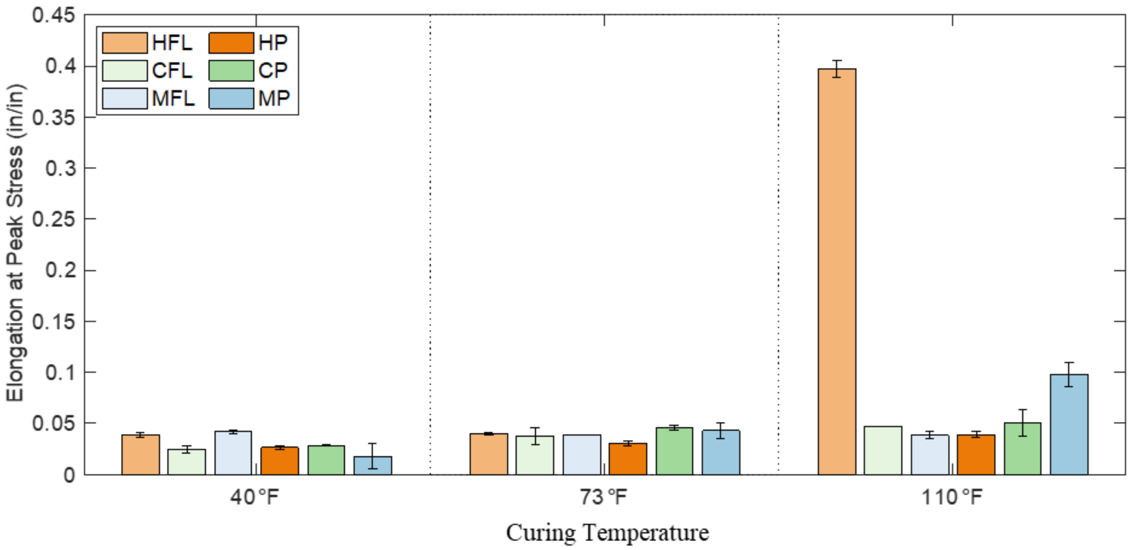
Figure 14 summarizes the compressive strength test results for all the structural fillers in terms of compressive strength and the elongation observed at corresponding stress levels at different curing temperatures. The standard deviations for each test result are plotted as error bars. As the Literature Review section discusses, increasing curing temperature mostly increases compressive strength and elongations at peak stress, and decreasing curing temperature generally results in decreases in these variables (Jahani et al., 2022). The decrease in compressive strength at low curing temperatures might be attributed to insufficient curing, possibly due to the limited cure time (7 days) and the slowed chemical process caused by the low temperatures impeding the curing mechanism. On the other hand, curing at higher temperatures can promote better cross-linking between the epoxy molecules, which enhances their mechanical properties. It can also accelerate the curing process.

Among all the structural fillers, HFL was most sensitive to curing temperature, with the highest compressive strength decrease at low curing temperatures and highest elongations before peak stress at high curing temperatures. The HFL manufacturer recommends a conditioning (curing) temperature of 65 to 75°F for the product. The higher curing temperature of 110°F was much greater than this recommended range, which is likely why the structural filler experienced much greater and undesirable elongation values at peak stress. This finding illustrates the importance of the manufacturer’s recommendations not only as these recommendations relate to curing temperature but other conditions as well. This upper limit on the manufacturer’s recommendation on curing temperature could easily come into play on hot summer days in Virginia.

When the research team compared the performances of all the structural fillers, the putty structural fillers generally exhibited higher compressive strength than the fluid structural fillers at each curing temperature. Among fluid structural fillers, MFL provided the highest strength at all curing temperatures, followed by CFL. HFL had the lowest strength at each curing temperature. On the other hand, HP exhibited the highest strength among putty structural fillers, and the compressive strength of MP was very close to HP at room and high curing temperatures. Nevertheless, HP had smaller elongations at these curing temperatures than MP. CP had the lowest strength at room and high curing temperatures. Overall, all the adhesives displayed average compressive strengths of at least 8 ksi across all curing temperatures, except for HFL at a 40°F curing temperature. This finding suggests that these adhesives all have sufficient strength to remain intact when used for preventive maintenance on steel bridges.



(a)



(b)

Figure 14. Graphs of (a) Compressive Strength; (b) Elongation at Peak Stress for Different Structural Fillers Cured at Different Temperatures. CFL = COPPS K-009; CP = COPPS K-082; HFL = Sikadur-32 Hi-Mod; HP = Sikadur-31 Hi-Mod Gel; MFL = Diamant MM1018; MP = Diamant MM1018.

Compressive Creep Results

Figure 15 shows average creep response of both fluid and putty structural fillers. HFL and CP recorded a high initial strain after approximately 100 to 150 hours. Similar to the compression testing results in Figure 12, HFL exhibited very low yield strength and experienced very high elongations at high curing temperatures. Although CP did not exhibit similar high elongations at high-temperature compressive strength testing, its elongations increased with increasing test temperatures. During compressive creep testing, CP exhibited the highest creep strains among all the structural fillers considered.

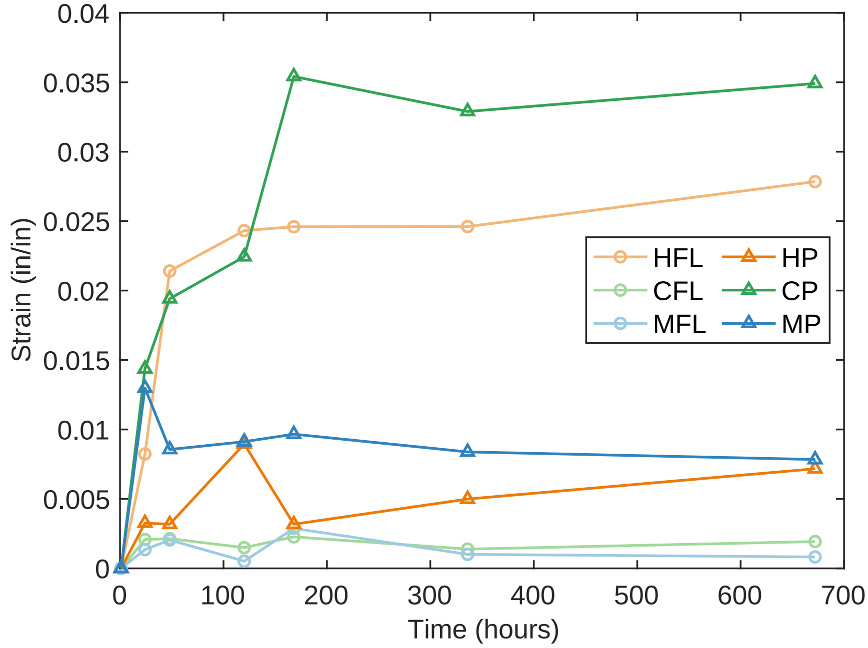


Figure 15. Creep Results of All Structural Filler Specimens. CFL = COPPS K-009; CP = COPPS K-082; HFL = Sikadur-32 Hi-Mod; HP = Sikadur-31 Hi-Mod Gel; MFL = Diamant MM1018; MP = Diamant MM1018.

The compressive creep results in Figure 15 illustrate that high curing temperatures can have a negative effect on the compressive creep performance of structural fillers. Recall that all these structural fillers were cured at 110°F. If the structural fillers used for bridge preventive maintenance were to be cured at similar temperatures, they could exhibit compressive creep, which can cause unwanted deformations. Therefore, curing temperatures for structural fillers used for preventive maintenance on bridges should follow the manufacturer's recommendations, particularly when temperatures are especially hot, such as in the summer.

Selection of Structural Fillers for Structural Component Testing

The research team used the results obtained from the compressive strength tests and compressive creep tests to reduce the number of structural fillers in the component testing from six to four. The purpose of this process was to eliminate structural fillers that did not perform as well as the others during the material testing. In particular, one fluid and one putty structural filler were eliminated from the rest of the experimental testing program. Among fluid structural fillers, HFL clearly exhibited significantly lower strengths at low curing temperatures while experiencing very high elongations at high curing temperatures. Also, HFL exhibited the highest creep strains among fluid structural fillers during compressive creep testing. Therefore, HFL was not considered for structural testing. For putty structural fillers, the compressive strength performance of the three structural fillers were all similar. Nevertheless, CP exhibited about 20% lower strength at room temperature than HP and MP. In addition, CP exhibited the highest compressive creep strains among all the structural fillers. Therefore, CP was not considered for further evaluation. Overall, CFL, MFL, HP, and MP were included in the component testing with structural fillers discussed in the next section.

Short-Term Compression Slip Test Results

Figure 18 shows the load versus slip displacement curves for all four specimen types with Class B blast-cleaned faying surfaces. The curves for both individual specimens (gray curves) and their averages are shown in the plots. The slip coefficient (k_s) for each specimen is also noted in the same plot.

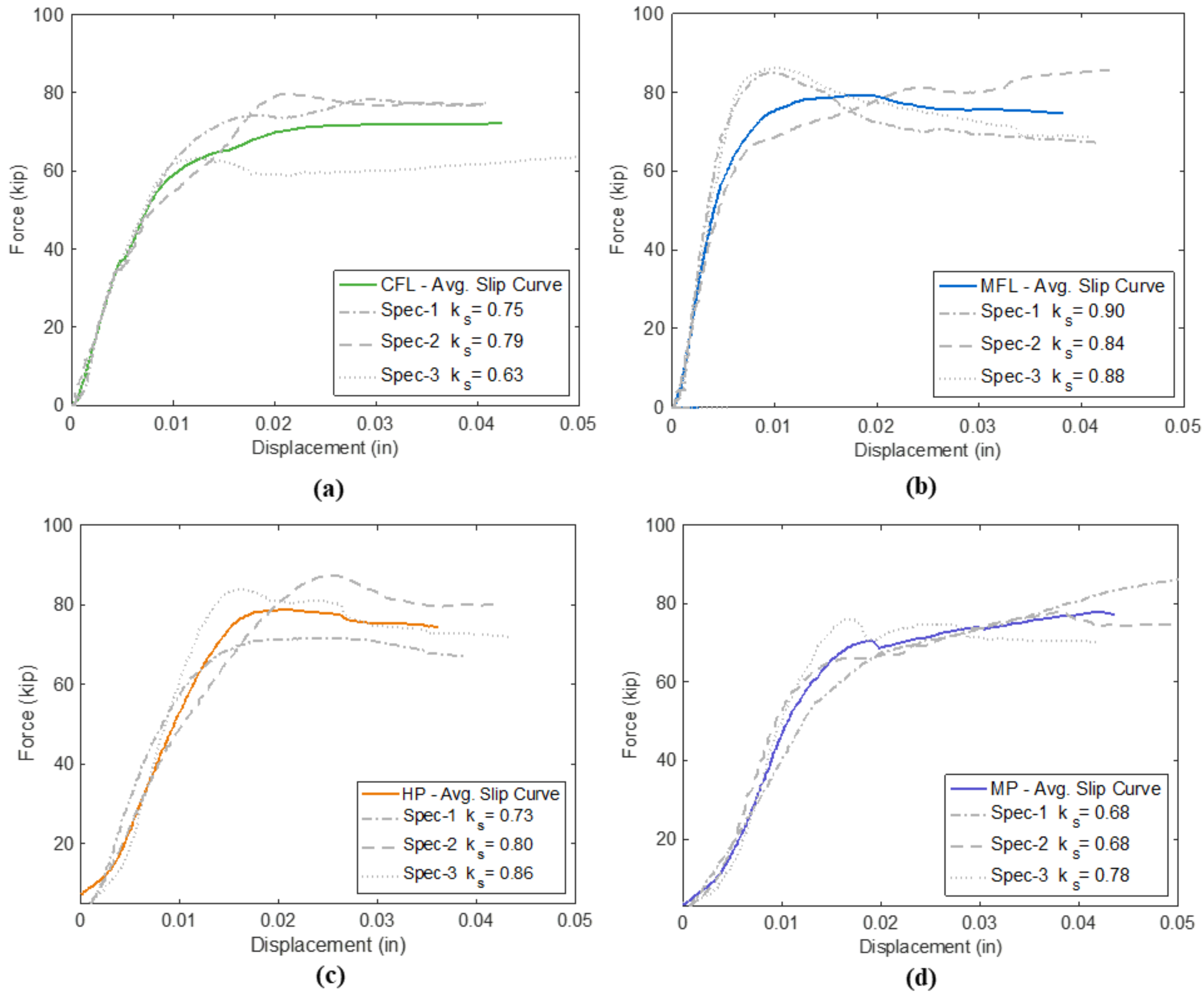


Figure 16. Load-Slip Displacement Curves of Individual Specimens and Their Averages for: (a) CFL; (b) MFL; (c) HP; (d) MP Structural Fillers with Blast-Cleaned Surfaces. CFL = COPPS K-009; HP = Sikadur-31 Hi-Mod Gel; MFL = Diamant MM1018; MP = Diamant MM1018.

The slip-load curves for individual structural filler specimens follow similar trends, with occasional variations. These variations can be attributed to seating issues when loading or defects within the samples. However, it is important to note that none of the variations had large effects on the slip-load results. Load-slip displacement for structural fillers with Class A organic zinc-coated faying surfaces are not shown here for brevity. The results for these fillers produced similar curves to those curves in

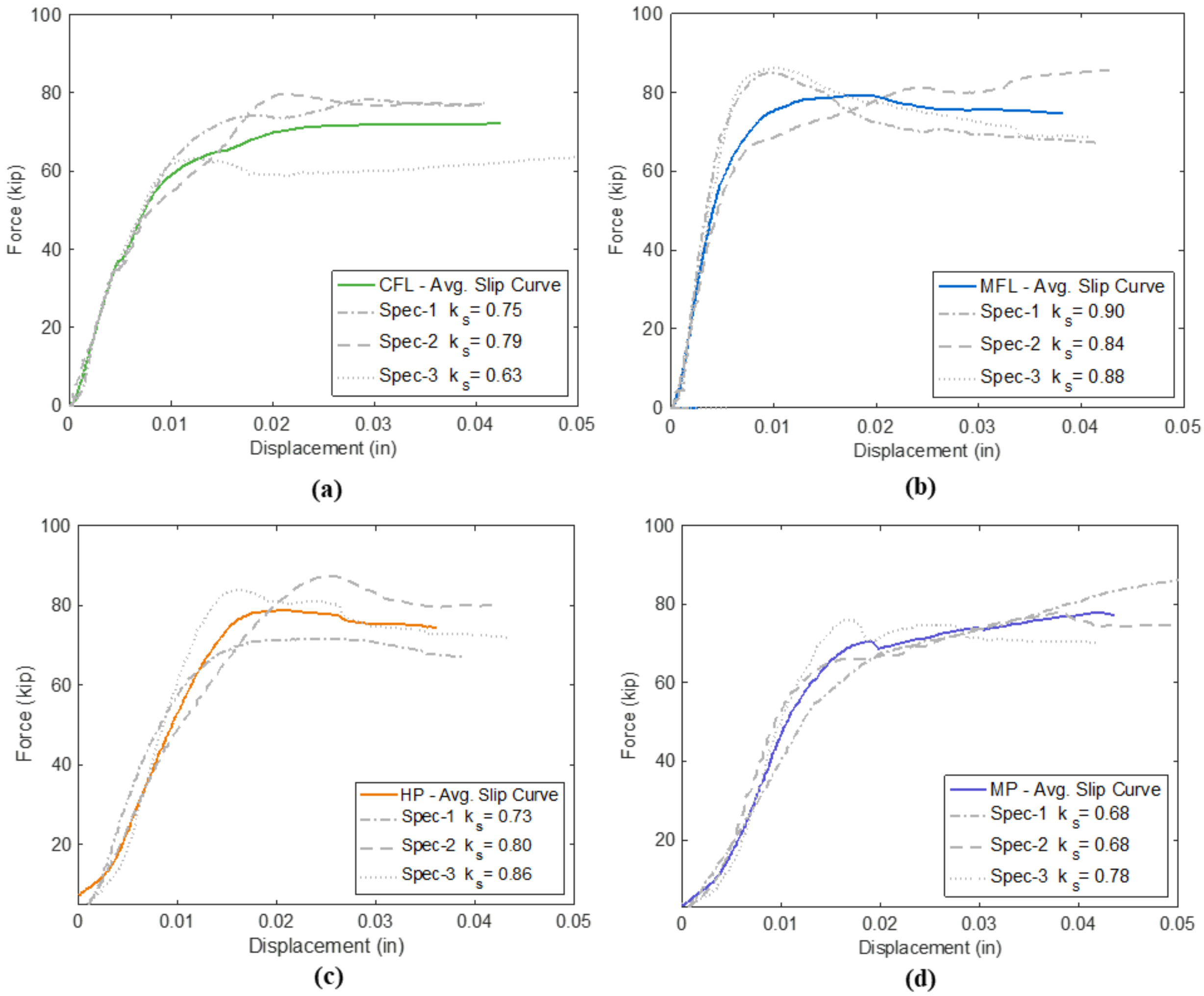
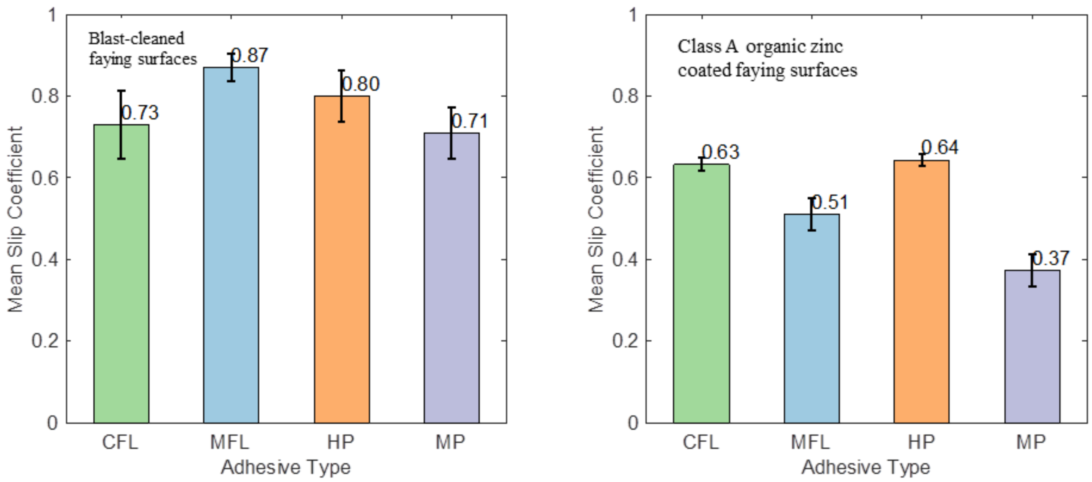


Figure 16, but their average maximum forces ranged from approximately 37 to 64 kips.

Figure 17 summarizes the mean slip coefficients and standard deviations for each type of structural filler for both blast-cleaned and Class A organic zinc-coated faying surfaces. According to AASHTO (2020), blast-cleaned faying surfaces must have a slip coefficient value of 0.50, and Class A organic zinc-coated faying surfaces must have a slip coefficient value of 0.30. As Figure 17a shows, the mean slip coefficient values for the structural filler specimens with blast-cleaned faying surfaces all easily exceed the minimum specified value of 0.50. In fact, all the average slip coefficient values exceed 0.71. Similarly, all the mean slip coefficient values for the structural filler specimens with the Class A organic zinc-coated faying surfaces all exceed the minimum specified value of 0.30.



(a) (b)

Figure 17. Mean Slip Coefficient and Standard Deviations for All Structural Fillers with: (a) Blast-Cleaned; (b) Class A Organic Zinc-Coated Faying Surfaces. CFL = COPPS K-009; HP = Sikadur-31 Hi-Mod Gel; MFL = Diamant MM1018; MP = Diamant MM1018.

For the fluid structural fillers, the MFL specimens had greater slip coefficient values for blast-cleaned faying surfaces, and the CFL specimens exhibited greater slip coefficient values for Class A organic zinc-coated surfaces. For putty structural fillers, the HP specimens exhibited greater slip coefficient values than the MP specimens. The MP specimens also had the lowest slip coefficient values among all four considered structural fillers, both for the blast-cleaned and Class A organic zinc-coated faying surfaces. The increased thickness of the structural filler layer (1/8 inch for fluid structural fillers versus 1/2 inch for putty structural fillers) could have contributed to this finding. Although this lower measure may have contributed to the lower performance of MP, such a relationship was not a general trend across all the testing. For example, HP (applied in 1/2-inch thickness) performed better than CFL (applied in 1/8-inch thickness) for the blast-cleaned faying surfaces and very similarly for the Class A organic zinc-coated faying surfaces. Therefore, the research team could make no conclusive determinations strictly by comparing fluid versus putty structural fillers.

Long-Term Tension Creep Test Results

The long-term tension creep tests were conducted only on the Class A organic zinc-coated faying surfaces because this type of faying surface provided the lowest slip coefficient values from the short-term compression slip tests, thus providing a worst case scenario. Class A organic zinc-coated faying surfaces are also most expected to be used for in-service bolted repairs, rather than blast-cleaned surfaces, because these surfaces provide corrosion protection.

Figure 18 shows the average slip in each tension creep specimen at more than 1,000 hours of continuous loading, referred to as creep deformation, for all structural filler specimens with the Class A organic zinc-coated faying surfaces. Results are reported for all three specimens per structural filler, except for MFL, for which data from one specimen could not be recorded, thus only two results are shown. Variations between specimens of the same structural filler are attributed to the structural filler not being perfectly homogeneous because of the mixing process and how well the structural filler filled the entire gap.

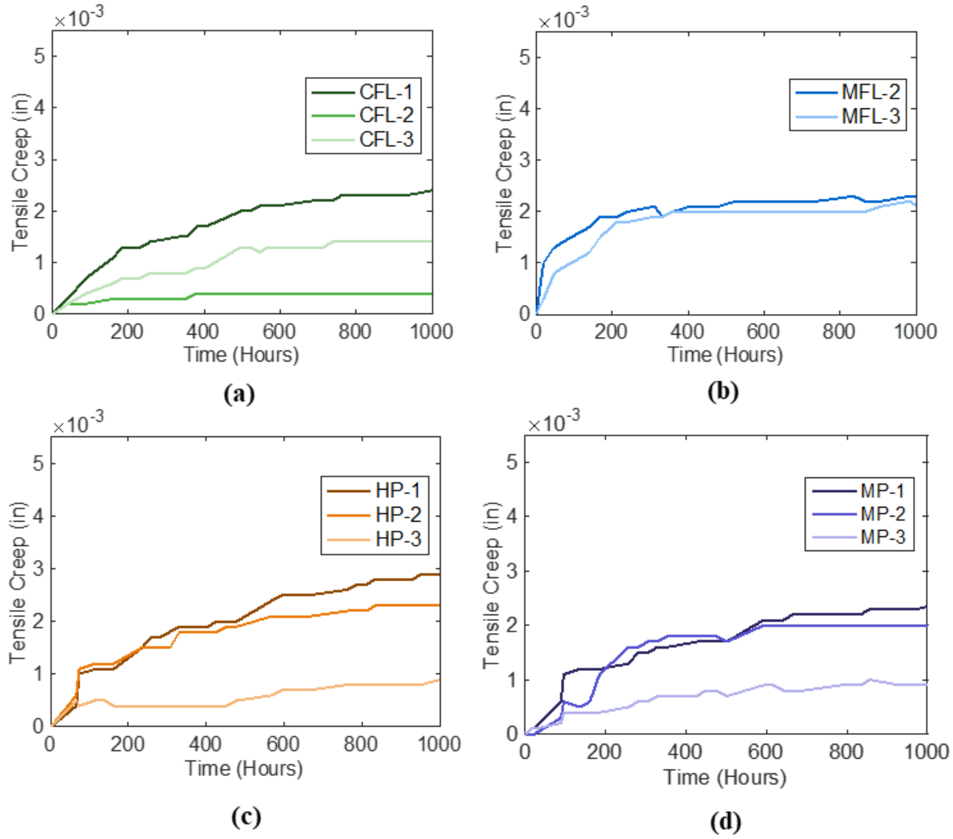


Figure 18. Tensile Creep Deformation Results for: (a) CFL; (b) MFL; (c) HP; (d) MP Structural Filler Specimens with Class A Organic Zinc-Coated Faying Surfaces. CFL = COPPS K-009; HP = Sikadur-31 Hi-Mod Gel; MFL = Diamant MM1018; MP = Diamant MM1018.

As Figure 20 shows, all creep deformations remained below 0.005 inches after 1,000 hours of testing, which is the creep deformation limit specified by RCSC (2020) for all types of faying surfaces to be used on slip-critical connections. Most of the deformations occurred within the first 200 hours. These variations are attributed to differences in the structural filler mixtures applied to the connections and variations in the relaxation of the clamping force across the specimens.

Although not required for the RCSC specification's tensile creep testing, the research team recorded and analyzed the clamping force in the bolts on each specimen. These results represent relaxation in the bolts (Figure 19). From the start of tensile loading through the 1,000 hours of testing, the average relaxation for each of the three specimens was 3%, 8%, 10%, and 13% for CFL, MFL, HP, and MP, respectively. Recall that the CFL and MFL specimens had a structural filler thickness of 1/8 inch, and the HP and MP specimens had a structural filler thickness of 1/2 inch.

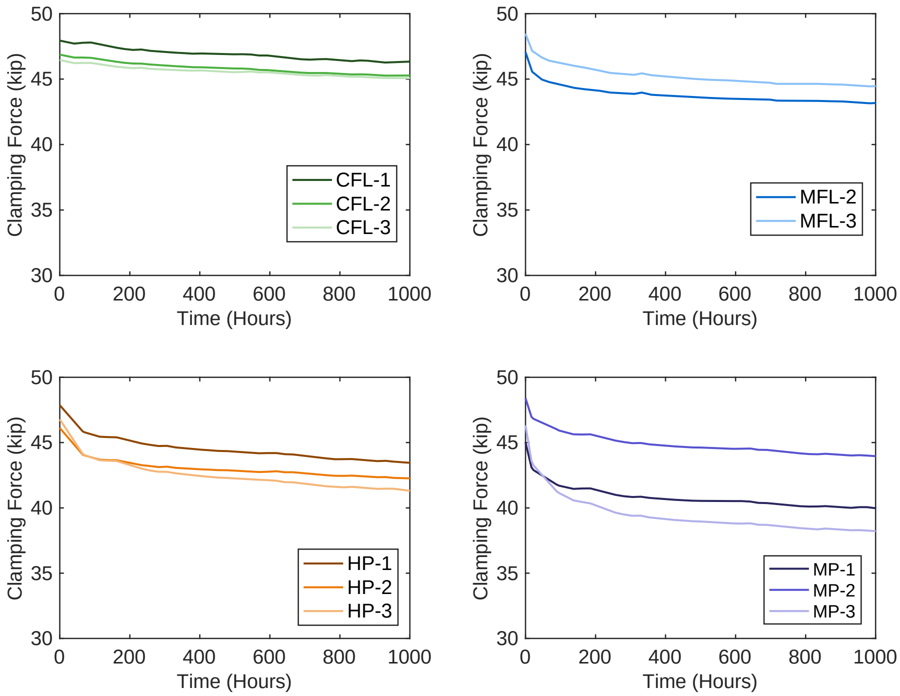


Figure 19. Relaxation in Bolt-Clamping Force in Each Specimen During Creep Tests for Different Structural Fillers. CFL = COPPS K-009; HP = Sikadur-31 Hi-Mod Gel; MFL = Diamant MM1018; MP = Diamant MM1018.

As the plots in Figure 19 show, most of the relaxation occurred within the first 100 to 200 hours for all the structural fillers, although this trend was most notable in the MFL, HP, and MP specimens. However, relaxation does not appear to reach a plateau in any of the specimens during the 1,000 hours of testing. This finding suggests that the relaxation in the bolt-clamping force would continue to increase if the tests were continued past 1,000 hours. When comparing the relative results between structural fillers of different types, the fluid structural fillers CFL and MFL exhibited smaller relaxation values than the putty structural fillers HP and MP. This finding is likely because the fluid structural fillers were only applied in 1/8-inch thickness compared with the 1/2-inch thickness of the putty structural fillers. This result was much more conclusive from the tensile creep tests than from the compressive slip tests. Overall, the CFL specimens appeared to exhibit the smallest relaxation values of the four structural fillers tested. These results are expected to be similar if Class B blast-cleaned faying surfaces were tested.

In summary, the relaxation values for all the structural fillers tested were relatively small, with a maximum average value of 13% for structural fillers applied in a 1/2-inch thickness. All the compressive slip tests on structural filler specimens also produced slip coefficient values and behavior exhibiting similar load versus slip curves compared with traditional bolted specimens with steel plates (RCSC, 2020). Therefore, cured structural fillers are expected to provide sufficient constructability, in terms of their strength and stiffness, to limit deformation of bolted parts when tensioning bolts on a bolted repair. This expectation is especially important for bolted repairs on beam sections with significant corrosion or section loss. When these types of repairs are constructed without using structural fillers to fill these gaps, the bolt tensioning process can cause undesirable bending to occur in either the existing beam section or the repair plates and can reduce the structural capacity of the repair. Therefore, using structural fillers in these cases is beneficial and can aid in the constructability and installation of good quality repairs. This use can be achieved by placing the structural filler to restore the deteriorated thickness and installing the surrounding bolted fasteners to a snug-tight condition. Then, after the structural filler has properly cured, the bolted fasteners can be fully tensioned.

However, all the structural filler specimens exhibited relaxation in their bolt-clamping forces ranging from 3 to 13%, and the relaxation did not reach a plateau during testing. Therefore, bolted connections with structural fillers used in this manner should not be expected to perform as slip-critical connections because the structural fillers were not functioning as incompressible materials, as is assumed in typical slip-critical bolted connections, contributing to clamping force relaxation. This caveat is important to consider when creating designs for these types of repairs. Relaxation of structural fillers could be better understood with future research efforts, including investigating the comparative relaxation of different types of structural fillers applied in different thicknesses and extending the test duration past 1,000 hours to determine if a load plateau is reached.

Summary of Material and Structural Testing Results

Figure 22 provides a color-coded summary of the results from the material and structural testing properties of the structural fillers that the research team evaluated. For HFL and CP, only the material testing was performed, so values corresponding to their structural testing properties are shown as not applicable. The color symbols indicate the percentile range of the result. Red is below 33% of the average, green is above 66% of the average, and yellow is within 33% of the average. The color symbols for the cost values do not follow this pattern and are subjective because the costs of MFL and MP were more than one order of magnitude greater than the other four structural fillers (Table 4), so the average cost values were highly skewed. Therefore, the research team assigned HFL, CFL, HP, and CP a green cost value and MFL and MP a red cost value. Additional details about the test results can be found in Starr (2024).

	HFL	CFL	MFL	HP	CP	MP
Compressive Strength, 40°F [ksi]	(red) 5.3	(yellow) 8.3	(yellow) 9.0	(green) 11.2	(green) 10.2	(green) 9.9
Compressive Strength, 70°F [ksi]	(red) 11.8	(yellow) 12.8	(yellow) 13.8	(green) 14.9	(red) 11.6	(green) 14.4
Compressive Strength, 110°F [ksi]	(red) 12.4	(red) 12.8	(green) 15.3	(green) 16.6	(yellow) 14.0	(green) 16.3
Elongation at Peak Stress, 40°F	(red) 0.0387	(green) 0.0245	(red) 0.0420	(yellow) 0.0262	(yellow) 0.0285	(green) 0.0178
Elongation at Peak Stress, 70°F	(yellow) 0.0401	(yellow) 0.0378	(yellow) 0.0387	(green) 0.0305	(red) 0.0458	(red) 0.0428
Elongation at Peak Stress, 110°F	(red) 0.3971	(green) 0.0469	(green) 0.0383	(green) 0.0390	(green) 0.0507	(green) 0.0975
Slip Coefficient (Blast-Cleaned)	*N/A*	(yellow) 0.73	(green) *0.87*	(yellow) 0.80	*N/A*	(yellow) 0.71
Slip Coefficient (Organic Zinc)	*N/A*	(green) 0.63	(yellow) *0.51*	(green) 0.64	*N/A*	(red) 0.37
Tensile Creep at 1000 h [in]	*N/A*	(green) 0.0014	(green) 0.0022	(green) 0.0020	*N/A*	(green) 0.0018
Clamping Force Loss at 1000 h	*N/A*	(green) 3%	(yellow) 8%	(red) 10%	*N/A*	(red) 13%
Cost	(green)	(green)	(red)	(green)	(green)	(red)

Figure 20. Color-Coded Summary of Material and Structural Testing Results for Structural Fillers. The color symbols indicate the percentile range of the result. Red is below 33% of the average, green is above 66% of the average, and yellow is within 33% of the average. CFL = COPPS K-009; CP = COPPS K-082; HFL = Sikadur 32 Hi-Mod; HP = Sikadur-31 Hi-Mod Gel; N/A = not applicable; MFL = Diamant MM1018; MP = Diamant MM1018.

Field Evaluation of Previous VDOT Preventive Maintenance Using Structural Fillers

The research team selected four bridges, each with previous preventive maintenance using structural fillers, for field evaluations and visual examinations. Two of these bridges were in VDOT's Richmond District and had bolted beam end repairs, with structural fillers used to restore corroded web thickness. The other two bridges were in VDOT's Northern Virginia District and had bearing preventive maintenance with structural fillers to repair gaps between a concrete abutment seat and steel masonry plates.

The two bridges in the Richmond District with bolted repairs were Federal ID 6041, Route 619 over Stony Creek, and Federal ID 5910, Route 1 of the CSX Railroad, both in Dinwiddie, Virginia. Both repairs were constructed around 2018 to 2019. The two bridges in the Northern Virginia District with bearing preventive maintenance actions were Federal ID 24993, Interstate 66 (I-66) Westbound over Cub Run, and Federal ID 24994, I-66 Westbound over Cub Run, both in Manassas, Virginia. Both preventive maintenance actions were performed around 2020.

Both VDOT districts had experience using multiple types of structural fillers. Table 5 and Table 6 show these structural fillers and their mechanical and application properties, respectively. The Richmond District noted a preference for using putty structural fillers as preventive maintenance in their bolted beam end repairs, such as Loctite® Steel Putty and Devcon® Steel Putty. The structural fillers were placed by troweling onto the bolted repair plates and then mating the repair plates onto the existing beam ends. In these cases, the main purpose of the structural fillers was to provide constructability and prevent bending of the repair plates during tensioning of the high-strength bolts. This process was achieved by first mixing the structural filler and troweling it onto the repair plates and then installing the repair plates onto the existing beam using snug-tight bolted assemblies. After that, bolts without structural filler within their grip length are fully tensioned, and bolts with structural filler within their grip length are left as snug tight. After the structural filler is cured, the bolts with structural filler within their grip length are fully tensioned. The Richmond District had tried fluid structural fillers, such as Loctite Liquid Steel, in the past, but these fillers were too runny to be effective. The putty structural fillers were stiff enough to remain in place until all three bolted repair plates had been installed. The district also noted that the contractor needed to quickly place the putty structural fillers after mixing them because they could set up quickly, especially on warm days.

The Northern Virginia District favored fluid structural fillers for bearing preventive maintenance because they were injecting the structural fillers into gaps between the top of the concrete abutment and the bottom of the steel masonry plate. A contractor had performed all preventive maintenance. For the first few uses of structural fillers, the district had used MasterFlow® 647 and MasterFlow 648 for the thinner and thicker gaps, respectively. However, availability challenges with these structural fillers led the district to begin using Sikadur-32 Hi-Mod. Notably, this same structural filler is designated as HFL in this report. HFL's properties are repeated in Table 5 and Table 6 for convenience.

When comparing the properties of the structural fillers VDOT has used for repair applications (Table 5 and Table 6) to the properties of structural fillers tested in this study (Table 3 and Table 4), the structural fillers used by VDOT have a similar range of both mechanical and application properties.

Table 5. Manufacturer-Reported Mechanical Properties of Structural Fillers Used on VDOT Preventive Maintenance Projects

Structural Filler Product Name	Product Type	VDOT District Used	Compressive Strength (ksi)	Elastic Modulus[a] (ksi)	Creep (inches/inch)	Tensile Strength (ksi)	Flexural Strength (ksi)	Shear Strength (ksi)
Loctite Fixmaster Fast Set Steel Putty EA 3473	Steel-Filled Epoxy Adhesive	Richmond	7.4	301	N/A	4.0	4.7	2.2 (lap shear on grit-blasted steel)
Loctite Liquid Steel EA 3472	Steel-Filled Epoxy Adhesive	Richmond	10.0	870	N/A	840	N/A	3.6 (lap shear on grit-blasted steel)
Devcon Plastic Steel Putty A	Metal-Filled Epoxy Putty	Richmond	8.3	850	N/A	N/A	5.6	2.8
MasterFlow 647	Epoxy Grout	NOVA	12.0 (7 days)	N/A	N/A	2.1 (7 days)	4.5 (7 days)	N/A
MasterFlow 648	Epoxy Grout	NOVA	13.8 (7 days)	2,180	< 0.024 inch after 3 months at 11.2 kips	1.5 (1 day on steel)	4.4 (7 days)	11.0 (50° at 7 days)
Sikadur-32 Hi-Mod (HFL)	Epoxy Adhesive	NOVA	11.8	210	N/A	6.9	7 (14 days)	6.2 (14 days)

N/A = not applicable; NOVA = Northern Virginia. [a]Under Compression.

Table 6. Manufacturer-Reported Application Properties of Structural Fillers Used on VDOT Preventive Maintenance Projects

Adhesive	VDOT District Used	Working Time[a] (minute)	Mix Ratio (A:B)	Viscosity	Intended Thickness Range (inch)	Intended Applications	Cost from Distributor
Loctite Fixmaster Fast Set Steel Putty EA 3473	Richmond	3.5–4	1:1 by volume	Putty	N/A	Ideal for emergency repairs, such as filling cavities, leveling machinery, and repairing cast-steel plates.	$712/gallon
Loctite Liquid Steel EA 3472	Richmond	40	1:1 by volume	Pourable	N/A	Rebuilding worn parts. Hard to reach areas. Anchoring and leveling.	$925/gallon
Devcon Plastic Steel Putty A	Richmond	45	2.5:1 by volume	Putty	N/A	Filling, rebuilding, and bonding metal surfaces.	$836/gallon
MasterFlow 647	NOVA	20–30	1.5:1 by volume	Epoxy grout	1/4-inch maximum	Injection or gravity feed to penetrate and fill voids. Grouted baseplates. Repair of cracked concrete.	$340/gallon
MasterFlow 648	NOVA	90–120	3.2:1:6.7 by weight	Epoxy grout	0.4–5.9 inch	Assembling and fixing industrial turbines, generators, compressors, and so on.	$119/gallon
Sikadur-32 Hi-Mod (HFL)	NOVA	30	1:1 by volume	Syrup	1.5-inch maximum lift	Machinery base-plate grout. Structural adhesive for concrete and metal.	$118/gallon

N/A = not applicable; NOVA = Northern Virginia. [a]At room temperature.

The research team visited the two bridges with bolted beam end repairs using structural fillers in the Richmond District, Federal ID 6041 and Federal ID 5910, in November 2023. Both bridges had numerous bolted beam end repairs for visual examination. Figure 21 features photos of one of the bolted repairs on Federal ID 6041. These repairs are constructed using a bent plate extending from the beam web onto the top of the bottom flange, rather than by the traditional method of using three separate repair plates for the web and top of the bottom flange. Using a bent plate provides an advantage by eliminating the potential crevice at the web-to-flange fillet formed when using two separate plates. However, the bent plate leaves an interior gap between the plate and the web-to-flange fillet weld. The fillers used appeared to provide good constructability and possess the required strength and stiffness to prevent any deformation of the repair plates or existing beams either during installation or while in service.

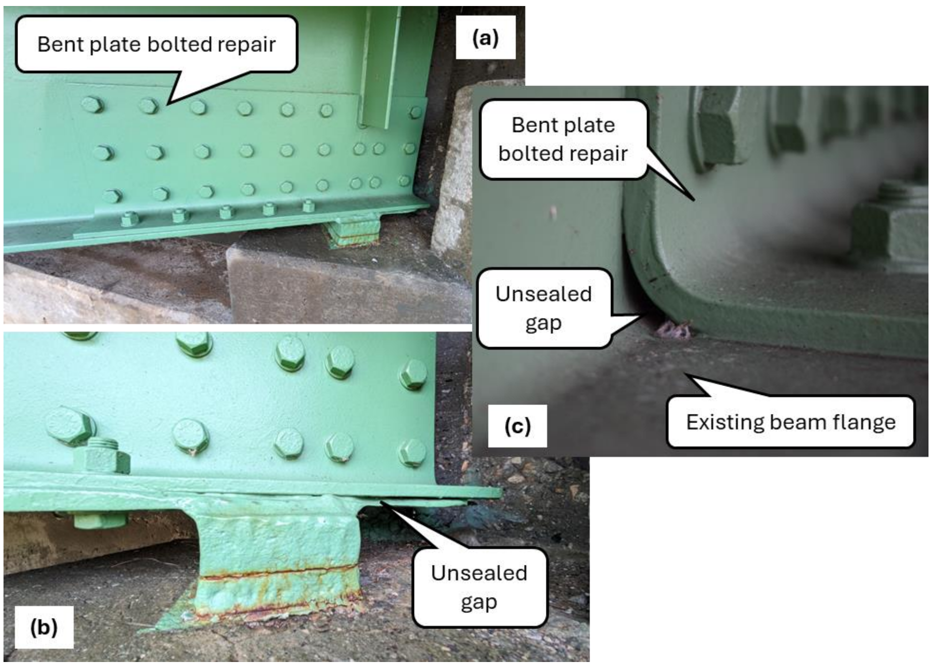


Figure 21. Photos of Bent Plate Bolted Beam End Repairs Using Structural Fillers on Federal ID 6041 Showing: (a) Overall View of Repair; (b) Closeup of Gap on End of Beam; (c) Closeup of Gap on Midspan Side of Beam

Although these repairs used structural fillers to fill gaps caused by corrosion on the existing beam, some instances of unsealed gaps were present in the repairs (Figure 21b and Figure 21c). These unsealed gaps were present, to some extent, in many of the repairs. Figure 21b shows an unsealed gap between the deteriorated existing beam flange and the bent repair plate at the end of the beam. Figure 21c shows an unsealed gap at the end of the bent repair plate. Water or deicing salt could potentially infiltrate these gaps and form crevices that could accelerate corrosion. These repairs could be improved by ensuring that these gaps are also filled with structural fillers. This objective could be accomplished by potentially placing more of the putty structural filler on the repair plate before installing it onto the existing girder before bolting it in place. Additional putty structural filler could also be placed in the gap after the bent plates were bolted into place, but this solution would require an extra operation from the contractor.

Figure 22 shows photos of the bolted repairs using structural fillers on Federal ID 5910. Because of the site geometry, the bolted repairs could not be visually inspected from close proximity. Therefore, gaps similar to those found on Federal ID 6041 could not be inspected. However, the bolted beam end repairs on this bridge also appeared to be functioning as designed, and no apparent structural deformations were present.

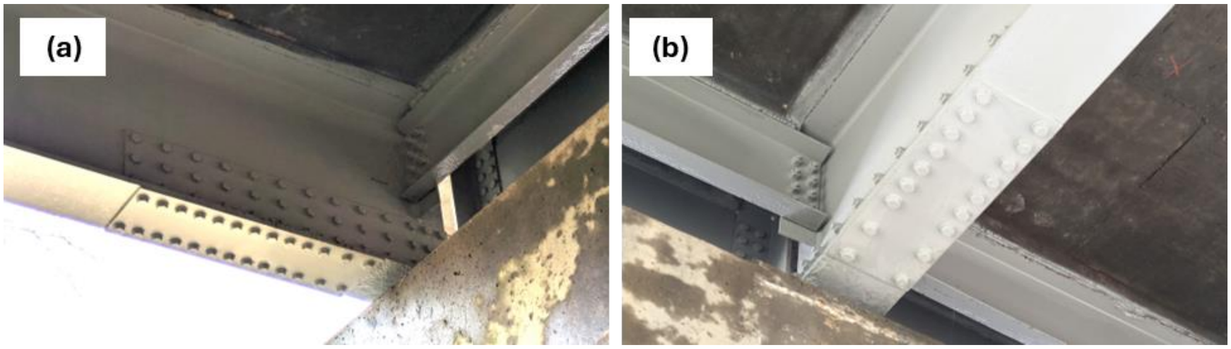


Figure 22. Photos of Bent Plate Bolted Beam End Repairs Using Structural Fillers on Federal ID 5910 Showing: (a) View from Side of Repair; (b) Bottom of Repair

The research team visited the two bridges with bearing preventive maintenance that used structural fillers in the Northern Virginia District, Federal ID 24993 and Federal ID 24994, in April 2024. Both bridges had several bearings with preventive maintenance for visual examination. Figure 23 shows example photos of how structural fillers were used for preventive maintenance. Researchers did not expect deformations at the bearings because of the large stiffness of both the concrete abutment and steel masonry plate. On some of the bearings, the edges of the injected structural filler could be seen, revealing a very small remaining gap between the concrete and steel. A gap of this size is likely not large enough to cause any concerns for future crevice corrosion.

Figure 23. Photos of Bearing Preventive Maintenance Using Structural Fillers on Federal ID 24993 and Federal ID 24994 Showing Gaps Filled with Adhesive between the Top of Concrete Abutment and the Bottom of Steel Masonry Plate

CONCLUSIONS

- *Structural fillers possess sufficient strength and stiffness to remain intact under compressive service loads when used for filling gaps or as steel grouting in the preventive maintenance of steel bridges.*

- *Structural fillers can improve the constructability of bolted plate repairs by resisting deformation of existing structure or repair plates during tensioning of bolted assemblies.* Structural fillers accomplish this objective by being placed to fill gaps between steel plates and being allowed to fully cure before tensioning bolted assemblies with structural fillers in their grip length.

- *Based on the results of this study, structural fillers cannot be considered incompressible so pretensioned bolts with structural fillers within their grip length should not be considered slip-critical.*

- *Structural fillers used for previous VDOT bolted beam end repairs and bearing preventive maintenance applications appear to be performing well after multiple years of field service.* The durability of these repairs or preventive maintenance actions can be ensured by fully sealing all gaps to minimize the potential for future crevice corrosion.

- *Structural fillers can experience greater elongation values at peak stress and compressive creep values when cured at high temperatures.* This issue can be alleviated by casting and curing structural fillers at temperatures within the manufacturer's recommendations. This consideration is especially important when temperatures are high on hot summer days.

RECOMMENDATIONS

1. *Virginia Transportation Research Council (VTRC) will develop draft guidance for VDOT to use structural fillers to improve the durability of bearing preventive maintenance and the durability and constructability of bolted beam end repairs for steel bridges for implementation into two special provisions and into the* VDOT Manual of the Structure and Bridge Division Part 2, Chapter 32.

IMPLEMENTATION AND BENEFITS

Researchers and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and to determine the benefits of doing so. This process is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

Regarding Recommendation 1, VTRC's initial draft guidance for using structural fillers on bolted beam end repairs and bearing preventive maintenance for steel bridges can be found in the Supplementary Material for this report. Following the publication of this report, VTRC will reformat this initial draft guidance into two VDOT special provisions and a section for addition into the *VDOT Manual of the Structure and Bridge Division Part 2, Chapter 32.* One of the special provisions will focus on using structural fillers for bolted beam end repairs and the other will focus on using structural fillers for bearing preventive maintenance.

Both the special provisions and the Chapter 32 addition will include recommendations on the following: specific structural fillers for use, structural filler type (i.e., fluid or putty) based on gap size, following the manufacturer's recommendations for structural filler use (including surface preparation, placement, curing, etc.), placement of structural filler to improve constructability and durability of repairs and preventive maintenance, further corrosion protection of the repairs or preventive (such as field or shop coating), sequence of placing structural filler and tensioning bolts for bolted beam end repairs, design and load rating bolted beam end repairs with structural fillers, and timeline for opening the structure to traffic. The guidance will also include a discussion on the pros and cons of using structural fillers compared with cementitious grouts. All three documents will be submitted to VDOT's Structure and Bridge Division and the VDOT Richmond and Northern Virginia Districts for their review within 6 months following the publication of this report. VTRC will then revise all three documents based on feedback and submit them to the Structure and Bridge Division for implementation.

Benefits

Using structural fillers can improve both the constructability and durability of bolted beam end repairs and bearing preventive maintenance on steel bridges (i.e., steel grouting). These benefits are achieved by the structural fillers' sufficient strength and stiffness to prevent deformations and sealing ability to prevent moisture and salt from infiltrating into a previous gap. To quantify these benefits, an abbreviated cost analysis was conducted on bolted beam end repairs and bearing preventive maintenance using structural fillers with assistance from the VDOT Richmond and Northern Virginia Districts, respectively.

Cost Analysis of Bolted Beam End Repairs Using Structural Fillers

The research team conducted an abbreviated cost analysis of previous bolted beam end repairs using structural fillers with assistance from VDOT's Richmond District. According to the district, bolted beam end repairs without any structural fillers typically cost between $50,000 and $75,000 per beam end. This cost increased from $10,000 to $15,000 per beam end a few years ago. This estimate includes materials, delivery, and installation labor of the repairs.

The cost increase of adding the structural filler to the repair was then estimated using some assumptions for a typical existing beam and bolted repair design. These assumptions included an existing beam web thickness of 1 inch, a bolted repair length of 5 to 7 feet, and the use of 1/2-inch-thick bent steel plates on either side of the existing web and a 1/2-inch-thick steel plate on the bottom of the bottom flange. The corrosion damage in the existing beam was assumed to be 100% section loss in the web for a length of 3 feet. Using these assumptions, the amount of structural filler required to fill the gaps caused by section loss was estimated to be approximately 11 to 20 pounds, including some additional structural filler to cover other section loss areas and to account for waste. Based on recent structural filler purchases, this amount of structural filler costs between $1,000 and $1,800. This amount represents a cost increase of approximately 1 to 3% when including structural fillers in typical bolted beam end repairs.

Because the use of structural fillers in bolted beam end repairs is still a relatively new method, its estimated service life increase is unknown. However, as previously stated, structural fillers can improve both the constructability and durability of bolted beam end repairs by preventing the intrusion of water and deicing salt into a gap. Therefore, the likelihood of a bolted beam end repair with structural fillers failing prematurely because of constructability or durability issues is much less likely than a repair without structural fillers. If a repair were to experience a premature failure, it would need to be repaired again. In most cases, these improvements likely outweigh the modest cost increase of $1,000 to $1,800, or approximately 1 to 3%, of the cost of a typical repair. Based on the cost estimates, if using structural fillers can prevent a premature repair failure for at least 1 in approximately 50 typical bolted beam end repairs, then the associated cost increase can be justified.

Cost Analysis of Bearing Preventive Maintenance Using Structural Fillers

The research team conducted an abbreviated cost analysis of previous bearing preventive maintenance using structural fillers with assistance from VDOT's Northern Virginia District. The district reported that bearing preventive maintenance with structural fillers was typically done as a corrective action. All the preventive maintenance had been part of larger contracts, and the structural filler portions of the repairs were not listed as pay items on the contracts. Therefore, the exact cost of the structural filler portion of the repair was not available. However, the district reported that the structural filler material and installation labor were both small costs, so they resulted in minimal overall costs.

One benefit of using structural fillers for bearing preventive maintenance is that jacking the bridge girders is not required because the structural filler can be injected into place. If a cementitious grout were to be used for this bearing preventive maintenance, the bridge girders would have to be jacked before the cementitious grout could be placed. This requirement is because the maximum aggregate size in the cementitious grout is larger than the typical gap heights found in these applications, so the cementitious grout would not be able to flow into and fill the gap. Jacking a bridge girder is known to be an expensive process, so it is likely that the cost of using structural fillers to fill these gaps would be less than the cost of jacking the bridge girder. Contractors using structural fillers and inspectors have noted that applying the structural fillers has been a relatively simple process. Therefore, installing these structural fillers is likely much simpler and cheaper than jacking a bridge girder to perform bearing preventive maintenance.

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