Task 1 Report – Literature Review

USE OF FIBER-REINFORCED POLYMER COMPOSITES FOR BRIDGE REPAIRS IN MONTANA

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1. INTRODUCTION

The focus of this research is to investigate the potential of Fiber Reinforced Polymer (FRP) composites to repair deteriorating members on bridges in Montana. This includes identifying the most promising applications of FRP technology for use in the state and filling in any minor research gaps that may inhibit their use. Ultimately, this project will culminate in an implementation project that uses the most relevant technology in an actual bridge project in Montana.

The specific tasks associated with this research are as follows:

Task 0 – Project Management

Task 1 – Literature Review and Identification of Pursued Application

Intermediate Technical Panel Meeting Task

Task 2 – Close Minor Research Gaps

Task 3 – Implementation

Task 4 – Monitoring Bridge Performance

Task 5 – Analysis of Results and Reporting

This report documents the work completed as part of Task 1 – Literature Review and Identification of Pursued Application. It should be noted that the literature review will continue to be updated as research progresses, and the updates will be included in the final report. This report outlines the use of FRP in bridge strengthening and repair projects by researchers and other state agencies and discusses the critical findings including surface preparation techniques, application methods, and performance in extreme environments. This report will be used to guide discussions and decide on which application(s) will be pursued during Tasks 2-4 of the current research, and ultimately determine the implementation timeline.

2. BACKGROUND

In the early 1970s, FRP started being used as a construction and repair material for bridges in the United States [1]. The Federal Highway Administration (FHWA) and the National Science Foundation (NSF) increased funding for research on FRP materials for infrastructure applications in the late 1980s after observing the growing acceptance of advanced composite materials in various fields (e.g., aerospace and sporting goods industries) [2]. Since then, increased research and development have led to the introduction of FRP materials being used in pedestrian and vehicular bridges. FRP offers significant potential as a corrosion-resistant construction/repair material, and the application processes require less installation time resulting in minimal road closures. Furthermore, some research suggests that a bridge can remain functional during the repair process, as traffic loading does not affect the strength of the FRP bond [3, 4]. As a result of this initial research and the known benefits of this material, several state departments of transportation (DOTs) have started investigating the use of FRPs as a bridge repair method in recent years.

The current project aims to investigate the efficacy of various FRP techniques and identify potential suitable methods for repairing/strengthening bridges in cold regions. One primary focus is on filling any research gaps that may impede the use of FRP in a chosen application in order to facilitate successful implementation. The ultimate goal of this project is to apply the chosen application and methodology on a bridge project in the state and monitor its performance. This proposed research is a necessary step to fully understand and capitalize on the benefits of using FRP for repairing/strengthening, and to subsequently increase the performance and durability of Montana bridges. The remaining sections of the current literature review are on the several types of FRP application techniques, anchorage systems, and a review of current Montana bridges with FRP repairs.

3. FRP APPLICATION TECHNIQUES

There are several techniques available for applying FRP to structural elements, such as external wrapping, Near Surface Mounted (NSM) bars, FRP laminates, and mechanically fastened FRP strips. Each of these techniques has its own benefits and shortcomings. A brief overview of the techniques and some research performed with these methods is included in the following sub-sections.

3.1 External wrapping

External wrapping with epoxy resin is one of the most common methods of using FRP for strengthening and repairing. There are three main processes of applying FRP externally for strengthening: wet layup systems, prepreg systems, and precured systems [5, 6]. Among these methods, the wet layup method is most popular because of its easy application process and smaller time requirement [6-8]. The process can be briefly described with the following four steps: 1) prepare the surface of the existing structure, 2) apply the epoxy resin to the surface, 3) place fiber fabrics on the structure surface, and 4) apply the epoxy resin on the fiber fabrics [8]. The process of applying FRP by the wet layup method is further detailed in ACI (American Concrete Institute) 440.2R-17 [9].

3.2 Near Surface Mounted (NSM) bars

NSM bars are another form of FRP strengthening and are a comparatively newer technique among the FRP application methods. Aiswarya and Prabhakaran described the NSM technique as cutting a series of shallow channels on concrete or masonry surfaces in the desired direction and then placing reinforcements into the channels after partially filling with epoxy mortar [10]. This technique has been used for strengthening beams [11-13], columns [14], and beam-column connections [15].

3.3 Laminates

The method of strengthening existing concrete structures with FRP laminates includes preparing the concrete surface and attaching FRP laminates to the concrete with an epoxy resin system. Significant works using the lamination method have been focused on strengthened beams [16-18] and columns [7, 19].

3.4 FRP strips

FRP strips, which are fastened mechanically to the surface of the structure, is another method of using FRP to strengthen/repair deteriorating structures. FRP strips require less installation time compared to other FRP strengthening techniques and do not require skilled labor. FRP strips are commercially available in varied sizes. Researchers describe the following application process of FRP strips: 1) predrill or mark the fastener location on the FRP strip, 2) clean the surface of the structure, 3) place and clamp the FRP strip on the structure surface, and 4) fasten the FRP strip to the structure with bolts [20, 21]. Selecting bolts is critical while strengthening with FRP strips. Many smaller bolts distribute the loads more evenly than fewer numbers of larger bolts [20]. FRP strips have been used to increase flexural capacity of concrete girders [20, 21] and to improve composite action of timber double caps [22].

3.5 Anchorage systems

Debonding is one of the main concerns when applying FRP techniques; however, this risk can be mitigated by providing anchorage. Examples of different anchorage systems are shown in Figure 1 – Figure 4. Kalfat [23] discussed several anchorage systems for different FRP applications techniques including U-wrap, mechanical fastener, nailed metal plates, concrete embedment, and fiber spike anchorage. Figure 1 shows an example U-wrap layout. Pham and Hao [24] showed that applying additional layering in the transverse direction can help mitigate debonding. They also described eliminating stress concentrations and thus improving the strengthening effectiveness and delaying premature debonding. Their researchers used longitudinal FRP for flexural resistance and transverse FRP for resistance to premature debonding. This same strategy was also employed in the past research at MSU previously discussed in the proposal of the current project. Lee mentioned that the angle and number of transverse wraps are two of the key parameters for mitigating longitudinal FRP debonding [25]. This study also showed that multiple 90^o U-wraps provide better ductility, whereas 45^o U-wraps can maximize overall capacity. Researchers also discussed the FRP spike anchorage (Figure 2), a comparatively newer anchorage system [23, 26]. This anchorage system has two parts: the anchor dowel that is inserted into a predrilled hole, and the fan that is fanned out and epoxied over the external wrapping. This technique is more flexible than U-wrapping, in that it can be easily applied on wide elements such as walls and slabs [23]. Anchorage is required at the ends of FRP NSM bar applications (Figure 3) to prevent slippage of the FRP bar. Anchorage is also necessary for prestress NSM systems to reduce the prestress loss [27]. Anchorage (bolts) is often used at various locations (primarily at the ends, Figure 4) to grip the FRP laminates [6, 28]. Al-Mahaidi and Kalfat presented two types of anchorage systems for FRP laminates to strengthen the web flange interface and combined shear and torsional strengthening [29]. To prevent the brittle failure of structures strengthened with FRP strips, several researchers recommended providing mechanical anchorage at the ends [20, 30].

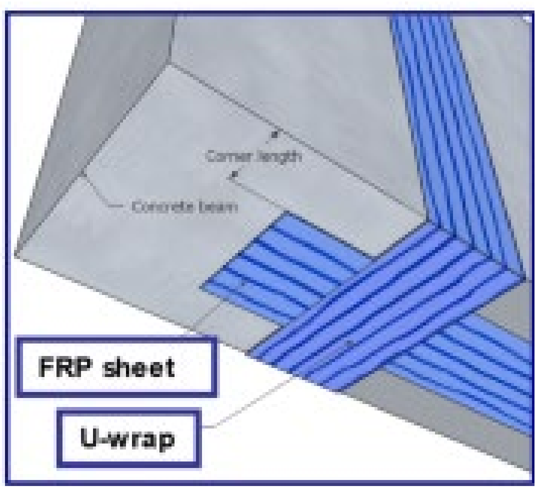


Figure 1: Example U-wrap FRP anchorage system [25].

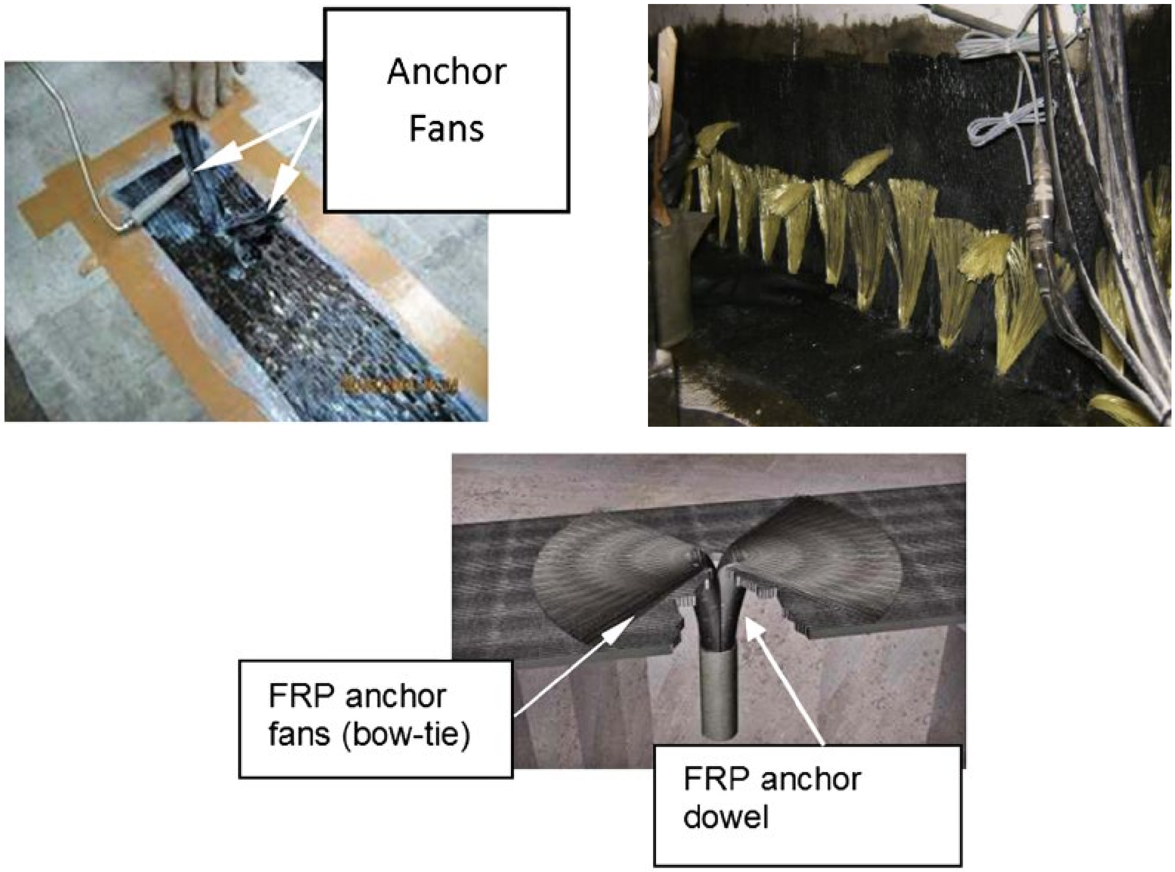


Figure 2: Example FRP spike anchorage systems [23, 26].

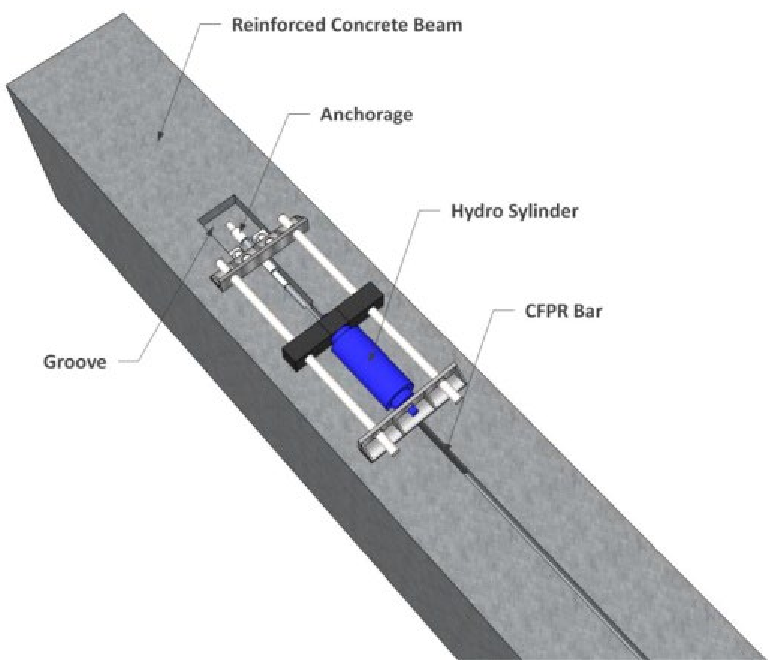


Figure 3: Example anchorage system for NSM bar [27].

Figure 4: Example mechanical anchorage system [23].

4. TIMBER BRIDGE REPAIR WITH FRP

This section summarizes the application of FRP in timber bridge projects. Specifically, this section discusses the FRP repair of several timber bridge elements including girders, piles, and pile caps.

4.1 Girder Applications

This section specifically discusses three timber bridge projects that used FRP strengthening techniques to repair timber girders. Specifically, this section discusses (1) a timber bridge in Washington County, Colorado, (2) a covered wooden bridge in Sins, Switzerland, and (3) a timber railroad bridge in Moorefield, West Virginia. This section also includes an example of a new build bridge with FRP located in Delaware County, Iowa.

4.1.1 Timber bridge, Washington County, Colorado

The superstructure of the F-22-V bridge, located in Washington County, Colorado, was rated 4 (Poor Condition, FHWA 1995) in 2019 due to aging and deterioration [31]. The Colorado Department of Transportation (CDOT) sponsored a program to rehabilitate the deteriorated bridge. The three-span, 83-year-old timber bridge is supported by 14 Douglas-Fir girders (Figure 5). The design load used at the time of construction was H15. This program had three major aspects: (1) laboratory testing, (2) field application and finite element model evaluation, and (3) load ratings.

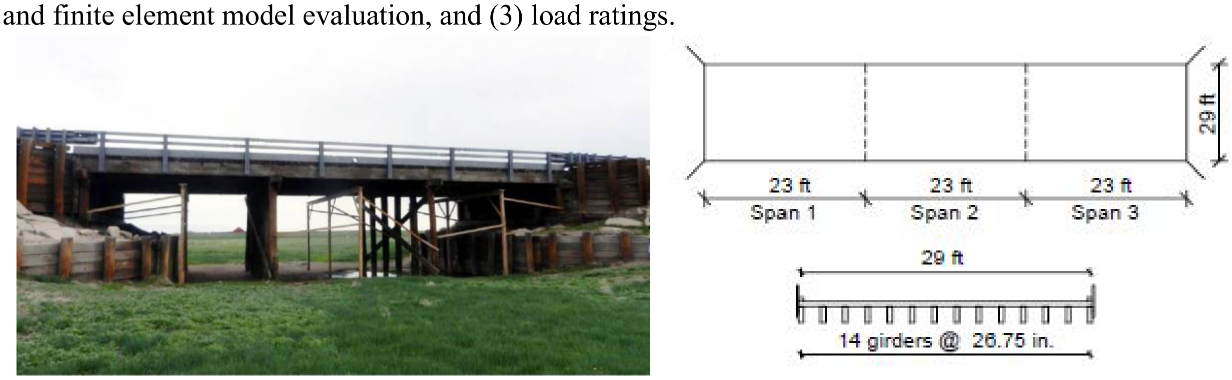


Figure 5: F-22-V bridge, Washington County, Colorado [31].

Three retrofitting techniques were evaluated in the laboratory testing section which included lag bolts, CFRP sheets, and hollow structural section (HSS), shown in Figure 6. The timber girder specimens were obtained from a decommissioned bridge that had similar characteristics to the retrofitted bridge. The girders were scaled down (6 in. x 6.7 in. x 130 in. long) by saw cut to match the testing space and actuator capacity. Each retrofitting technique was tested three times, and the responses of the 12 girders (Table 1) were evaluated.

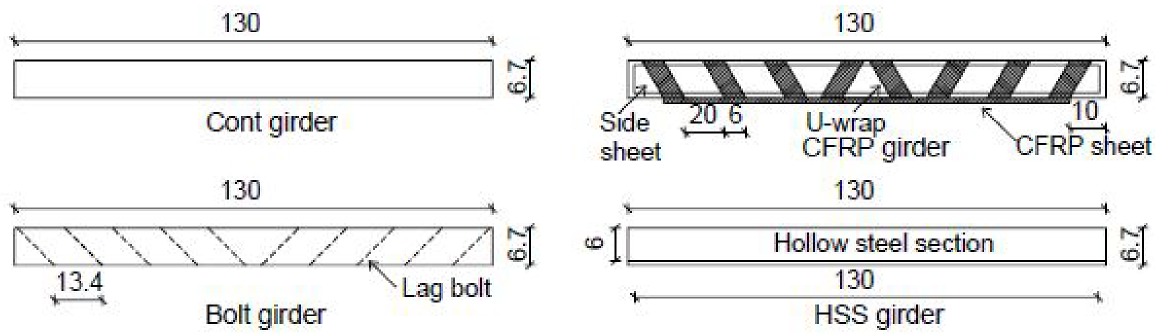


Figure 6: Control and strengthened girder specimens [31].

Table 1: Girder configurations [31].

Girder	Retrofit	Ultimate load (kip)		Modulus of rupture (psi)	
		Individual	Average	Individual	Average
Cont-1	None	9.26	8.72	5,482	5,154
Cont-2	None	8.00		4,728	
Cont-3	None	8.88		5,250	
Bolt-1	Lag bolts	6.68	7.01	3,945	4,143
Bolt-2	Lag bolts	7.06		4,177	
Bolt-3	Lag bolts	7.28		4,307	
CFRP-1	CFRP	9.33	9.55	5,526	5,647
CFRP-2	CFRP	10.07		5,961	
CFRP-3	CFRP	9.24		5,453	
HSS-1	Steel beam	22.41	22.35	13,256	13,223
HSS-2	Steel beam	20.30		12,009	
HSS-3	Steel beam	24.35		14,402	

A unidirectional CFRP sheet with a thickness of 0.013 in. was used for the CFRP strengthening technique. The CFRP sheet has a yield strength of 109 ksi. An epoxy resin consisting of a resin and hardener mixture was used at a mass ratio of 4:1 as the adhesive. The application process of the CFRP sheet to the girders includes cleaning the bottom and the side of the girders with a wet towel and fully drying them before the epoxy application. A single layer of the CFRP sheet (4 in. wide) was attached at the tension phase. U-wrap CFRP sheets (6 in. width) at an angle of 30^{o} and one more layer of side sheets was applied to prevent premature debonding failure. The retrofitted girders were cured at room temperature for 7 days before testing. Lag bolts (0.75-in-diameter) were used for the bolt-strengthened girders. The bolts were placed at an angle of 45^{o} in the predrilled hole on the girders, and the extra portion of the bolts was cut off. For the HSS strengthened girders, the 2 in. x 6 in. x 0.25 in. thick HSS sections were precut to 130 in. and predrilled in the middle and near the ends. Then they were attached to timber girders with washers and nuts. The girders underwent a four-point bending test and were loaded at a rate of 0.039 in./min until they failed. The test setup is shown in Figure 7. To monitor the strain, transducers were positioned 0.8 in. from the top and bottom of the girders. Additionally, a digital image correlation (DIC) technique was used to visually track the damage progression. The capacities of the CFRP and HSS strengthened girders exceeded the control girder's capacity by 9.5% and 156.2%, respectively. However, the bolts initiated local failure, resulting in the bolt-strengthened girder having a 19.6% lower capacity compared to the control girder. The amount of dissipated energy increased in all retrofitted girders.

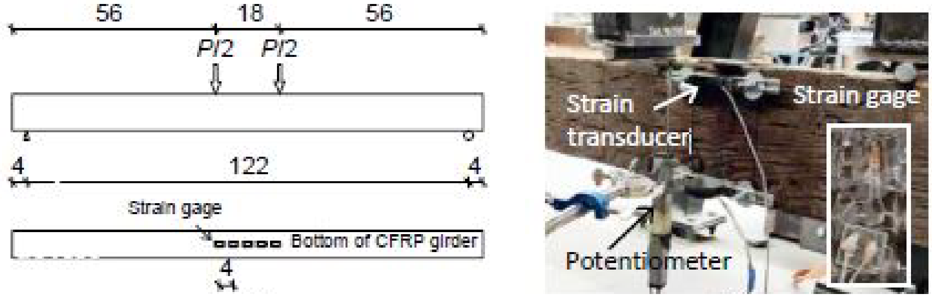
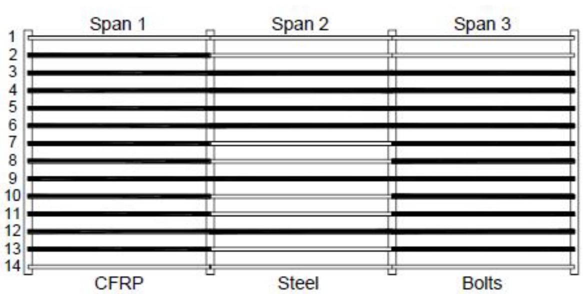
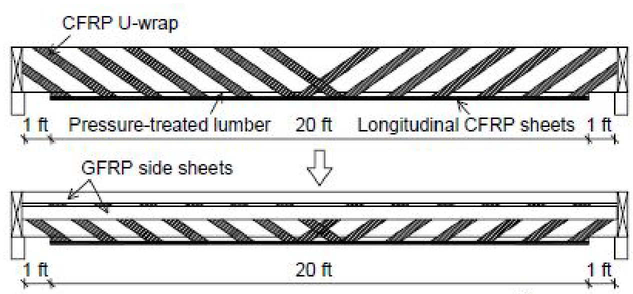


Figure 7: Test setup [31].

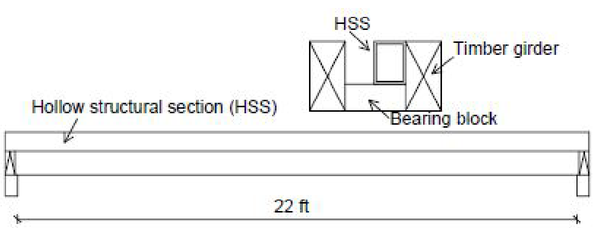
The next section of this report focused on strengthening several girders of the F-22-V bridge with CFRP sheets, lag bolts, and HSS (Figure 8). The bridge was load tested with a truck, and its responses were recorded and compared with the responses from three-dimensional finite element models. The strengthening processes were similar to those tested in the lab. Two layers of 4-in. wide unidirectional CFRP sheets were bonded with an epoxy adhesive on the bottom of the girders after cleaning and drying the girder surface. CFRP U-wrap (6 in. wide) was provided at a spacing of 20 inches. The GFRP sheet was also bonded to the sides of the girders to prevent premature debonding. ASTM A500 Grade C HSS beams (12 in. x 8 in. x 5/16 in.) were mechanically fastened with the timber at both ends and midspan using threaded rods. ASTM A354 Grade BC threaded bolts were embedded through 45° predrilled holes with an impact wrench. A Type 3 legal truck was used for the load testing, and there were two scenarios: a) unloaded truck (28 kips), and b) loaded truck (60 kips). The truckload was applied to a location near the exterior girder (the distance between the inside curb face and the rear axle outside tire was 25.4 in.) where the maximum bending moment would be generated. LVDTs were placed underneath the girders to monitor the girders' downward deflections.



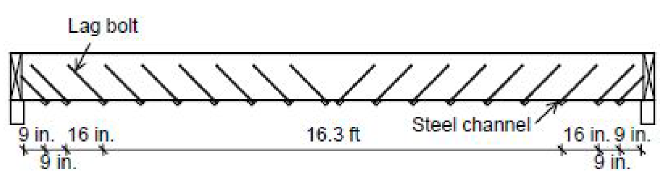
(a) Bridge spans.



(b) CFRP sheets.



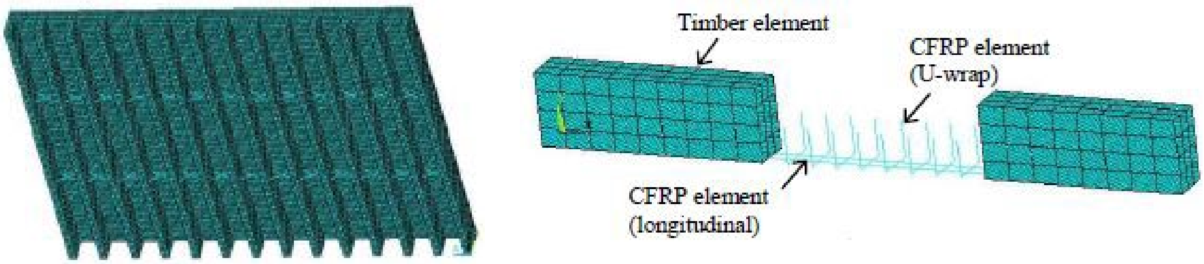
(c) HSS.



(d) Lag bolts.

Figure 8: Bridge strengthening [31].

Three-dimensional finite element models were constructed using ANSYS to represent the F-22-V bridge with and without strengthening (Figure 9). In this analysis, the timber was modeled using eight-node structural solid elements (SOLID185). The transverse bracings of the bridge superstructure, the steel strips connected with lag bolts, the HSS beams, the unidirectional CFRP sheets, and the pressure-treated lumber strips were simplified using spar elements (LINK180). Properties of timber (Table 2) and CFRP (Table 3) from several previous studies were used to validate the model.



(a) Full-scale bridge model. (b) Girder model.

Figure 9: Model development [31].

Table 2: Properties of timber girders for model validation [31].

Reference	Dimension			Material properties						
	Width (in.)	Depth (in.)	Length (ft)	E_L (ksi)	E_T (ksi)	E_R (ksi)	G_{LT} (ksi)	G_{TR} (ksi)	G_{LR} (ksi)	MOR (ksi)
Gentile	4	12	14.1	1,100	55	75	86	7.7	70.6	2.87
Yang	3	12	19.7	1,560	78	106	122	10.9	99.9	4.48
Rescalvo	3	6	4.3	1,740	86	118	135	12.2	111	4.32
Nziengui	2.3	7	13.3	2,850	142	193	222	19.9	182	N/A*
Halicka	5.5	8	11.2	1,190	60	81	93	8.4	76	N/A**

Gentile = Gentile et al. (2002); Yang = Yang et al. (2016); Rescalvo = Rescalvo et al. (2017); Nziengui = Nziengui et al. (2019); Halicka = Halicka and Slosarz (2021)
*: test was ceased at a load of 4.59 kN
**: average test capacity of 19.8 kips was given

Table 3: Properties of CFRP for model validation.

Reference	t_f (in.)	f_{fu} (ksi)	ε_{fu} (%)	E_f (ksi)	v
Rescalvo et al. (2017)	0.047	320	1.22	26,110	0.3
Halicka and Slosarz (2021)	0.047	410	1.35	24,700	0.3

t_f = thickness; f_{fu} = tensile strength; ε_{fu} = rupture strain; E_f = elastic modulus; v = Poisson's ratio

Several key findings were obtained. The increased magnitude of the truckload resulted in greater dispersion in girder deflections and discrepancies between measured and predicted responses due to load placement above the girders. The probability of exceeding deflection limits per AASHTO standards was significantly reduced after strengthening the bridge. Among the three methods, the stiffening efficiency of the HSS option was higher at the system level while the use of CFRP was most efficient at the member level. The computational model's predicted live load distribution factors closely matched the measured factors, suggesting the use of the approach proposed by Fanous et al. (2011) as an alternative to AASHTO distribution methods [32].

The final portion of this project focused on the load ratings of two timber bridges retrofitted with HSS. Finite element models were formulated and validated under 17 live load specifications from the manual of a transportation agency and proposed a mechanics-based rating approach. The repair significantly improves girder capacity and timber allowable stress, reducing failure probability by up to 99.2% and emphasizing the importance of steel beam configuration and placement for enhancing repair system efficacy. No additional details are discussed here, as they are outside of the FRP application scope of the current project.

4.1.2 Covered wooden bridge, Sins, Switzerland

A covered wooden bridge near Sins, Switzerland, constructed in 1807, was initially designed for horse-drawn vehicles [33]. The bridge's western side was supported by arches strengthened with suspended and trussed members. The supporting structure on the eastern side consists of suspended and trussed members with interlocking tensioning transoms. The cross beams were constructed by placing two solid oak beams on top of each other. The lower beams were 14.6 inches (37 cm) deep and 11.8 inches (30 cm) wide; the upper beams were 11.8 inches (30 cm) deep and 11.8 inches (30 cm) wide. Twenty-ton vehicles were permitted for the bridge.

In 1992, the bridge required repairs. The Swiss Federal Laboratories for Materials Testing and Research (EMPA) worked on strengthening the beams using carbon fiber reinforced epoxy strips. They used two types of strengthening to reinforce the crossbeams: 0.04 inch (1 mm) thick, high-modulus M46J fibers carbon FRP (CFRP) strips, and 0.04 inch (1 mm) thick, high-strength T700 fibers CFRP strips. The M46J strips had a width of 9.8 inches (250 mm) at the top and 7.9 inches (200 mm) at the bottom, while the T700 strips were 11.8 inches (300 mm) wide at the top and 7.9 inches (200 mm) wide at the bottom. The properties of the strengthening materials are shown in Table 4.

Table 4: Properties of the CFRPs used in strengthening the Sins bridge, Switzerland [33].

Property	Strip type no.				
	1	2	3	4	5
Fibre type	66% T 300 34% E-glass	Carbon T 300	Carbon	Carbon T 700	Carbon M 46 J
Fibre volume fraction [%]	–	70	51	50	70
Longitudinal strength [MPa]	960	2000	1900	2100	2600
Longitudinal elastic modulus [GPa]	80	147.5	129	130	305
Strain at failure [%]	1.15	1.36	1.47	1.62	0.85
Density [g/ccm]	–	1.58	1.46	–	–

Prior to application of the strengthening technique, the surface was prepared with a portable system. Strain measurement devices were installed in selected crossbeams for post monitoring. Pulse infrared thermography was also installed to observe the bonding between the structure and the CFRP strips. Figure 10 shows pictures of the strengthened girder.

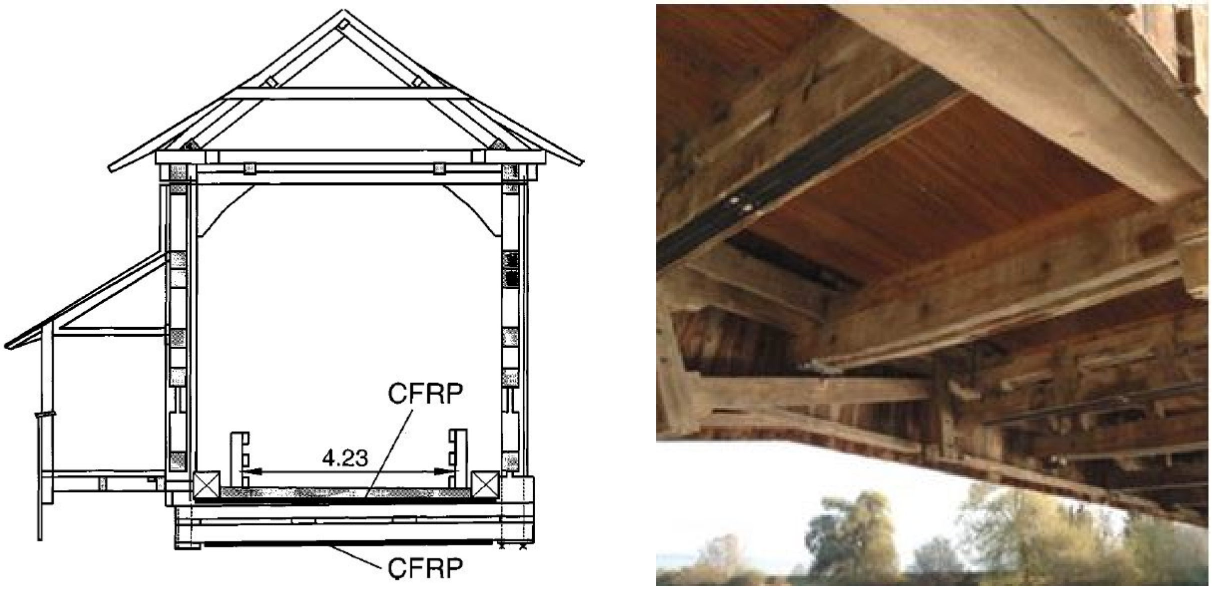


Figure 10: Strengthened girder in Sins bridge, Switzerland [33, 34].

The performance of the Sins bridge was satisfactory as of the year 2000. No significant damage was observed. Figure 11 depicts a photo of post monitoring.

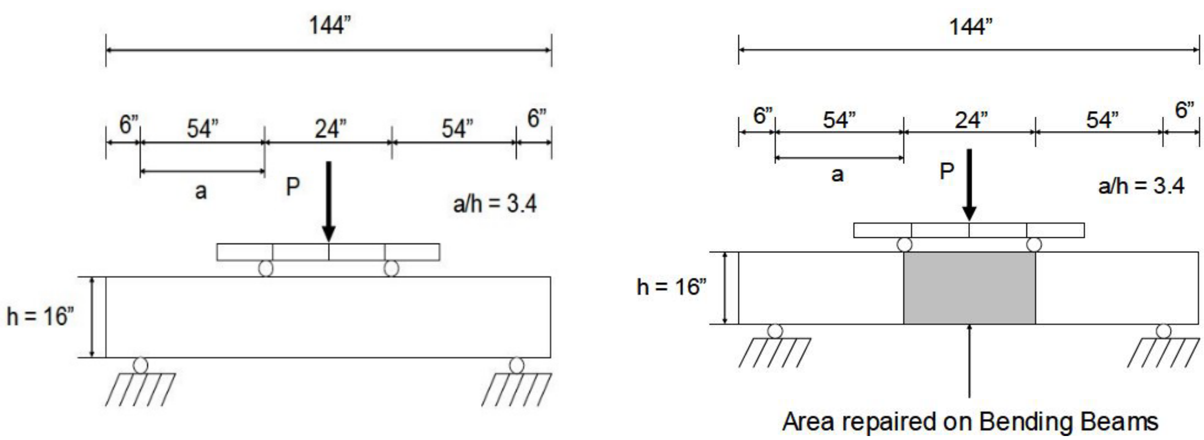
Figure 11: Post monitoring of Sins bridge, Switzerland [34].

4.1.3 Timber Railroad bridge, Moorefield, West Virginia

West Virginia University worked on load testing and rehabilitating two 50+ year old open deck timber railroad bridges located on the South Branch Valley Railroad (SBVR), Moorefield, WV [35]. The bridge consists of seven spans on eight pile bents. Each span length is approximately 12 ft (3.6 m) center to center of the supports and contains two main chords. The chords are supported by pile bents which consist of one pile cap and four piles. Figure 12 shows a photograph of one of the bridges.

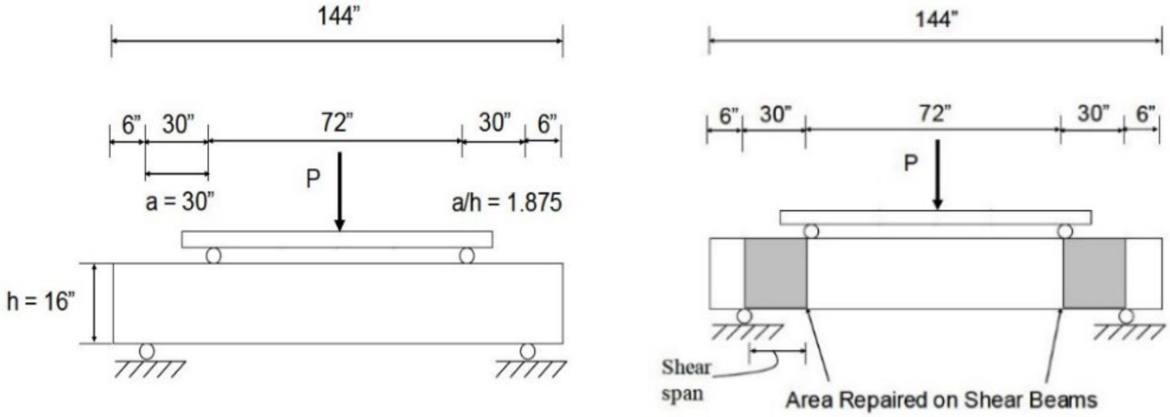
Figure 12: Photograph of timber railroad bridge in Moorefield, West Virginia [35].

The rehabilitation process of the bridges involved repairing the piles and pile caps with Glass FRP (GFRP) composite wraps, in combination with phenolic formaldehyde adhesives. To verify the strength and bonding capabilities of the repaired structure, a series of lab tests were performed before applying this in the field. Four full-scale, 8 inch x 16 inch x 12 ft (20.3 cm x 40.6 cm x 3.6 m) timber stringers were tested following the four-point bending configuration. Two control specimens were tested for failure in bending (Figure 13) and a second pair for shear failure (Figure 14). The specimens were then repaired in the maximum moment and maximum shear areas, respectively, using GFRP materials and phenolic-based adhesives. All the repaired beams were then retested in four-point bending.



(a) Before repair. (b) After repair.

Figure 13: Bending test setup for the railroad bridge project, Moorefield, West Virginia [35].



(a) Before repair. (b) After repair.

Figure 14: Shear test setup for the railroad bridge project, Moorefield, West Virginia [35].

These laboratory tests validated the effectiveness of phenolic adhesives in combination with GFRP when applied to creosote-treated beams and evaluated the load-carrying capacity of the repaired beams. The repaired beams performed well and regained reasonable shear and bending strength.

The field load testing was done before and after repairing the pile cap, stringer, and pile. The phenolic resin and formaldehyde hardener ratio used was 5:1 by weight. The pile cap and stringer repairing process involved removal of decayed material, rounding and sanding, priming the structure surface, coating of GFRP fabric with resin, and applying the GFRP wrap. The pile repairing process followed similar steps including removal of decayed material, construction of molding, placing of bulk filler, sanding, GFRP fabric application, applying pressure, and sealing. Load testing was done using a General Electric 80-ton locomotive (Figure 15) provided by SBVR. Tests were done using the locomotive at three different speeds (5, 10, and 15 mph) and dynamic responses were recorded. Static loading was performed by positioning the test locomotive at a specific place.

Figure 15: 80-TON SBVR Locomotive used for the Moorefield bridge field testing, West Virginia [35].

The GFRP composite with phenolic formaldehyde adhesives performed well. The GFRP composite material and timber bonds were adequate and overall, the strain distribution within the substructure of a timber railroad bridge was improved.

4.1.4 Example of a new build bridge with FRP (Delaware County Bridge), Iowa

Delaware County, Iowa, constructed a bridge comprised of FRP-reinforced glued-laminated timber girders and a transverse glued-laminated timber deck [36]. This system was chosen because it was economical, durable, and required less installation time. This bridge had a simple 64-ft (19.5 m) span with two lanes, and was 29 ft 7.5 inch (9 m) wide. It is located in Lime Creek, east of Ryan, Iowa. The superstructure is comprised of eight glued-laminated timber girders strengthened with FRP plates, and a transverse glued laminated timber deck (cross-section shown in Figure 16). The substructure consists of timber piles, timber abutment caps, and a timber plank abutment back wall.

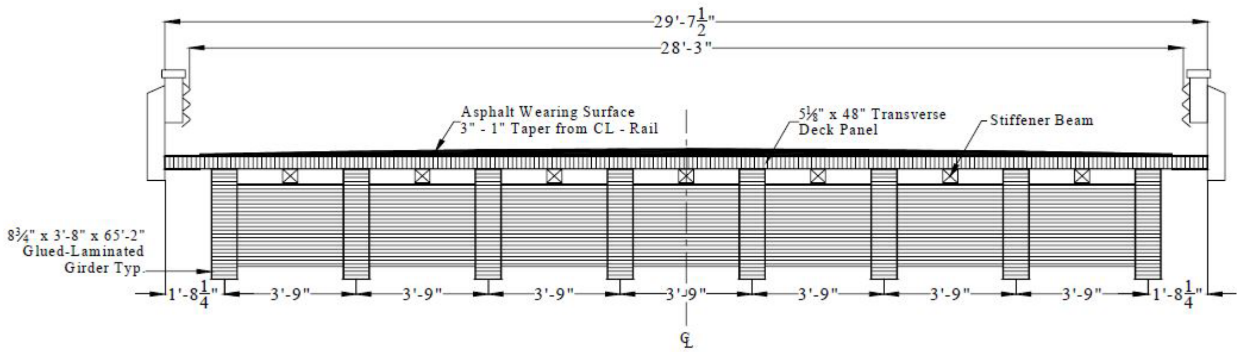


Figure 16: Cross-section of the Delaware county bridge [36].

After a preliminary inspection at the Alamco Wood Products, Inc. plant, Albert Lea, MN, the girders were planed, drilled, routed, and prepared for FRP applications. The FRP plates were 0.50 inch (12.7 mm) thick. There were no complications during the application of FRP. Standard deck panels were used for this bridge construction. After construction and prior to testing, another inspection was made. One girder (G1) bumped while handling, and there was a delamination of the first foot (30.5 cm) of the FRP plate. No significant defects were found during the inspection. The decks were well seated, but there were gaps in several locations between adjacent decks ranging between 0.25 inch (6.35 mm) to 0.5 inch (12.7 mm). The asphalt-wearing surface was also inspected before load testing. Some key points from the inspection include that no moisture-blocking membrane was installed between the glued-laminated deck, the wearing surface did not cover the entire deck, and small transverse cracks formed at each panel joint and at the abutments.

The bridge was instrumented (Figure 17) and the structural performance was evaluated through a series of loading tests conducted over a three-year period. Girder and deck deflections were accurately measured at critical locations using an Optim Megadec data acquisition system. Transducers were installed underside of all the girders and deck panel to measure the global and localized deflections, respectively.

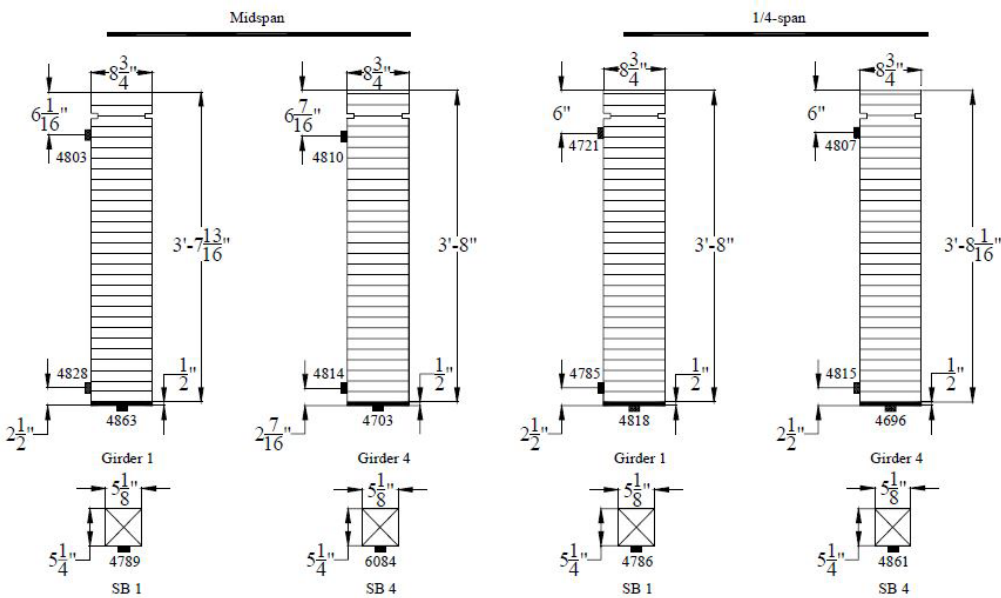


Figure 17: Position of the transducers on the Delaware county bridge girders [36].

The Delaware County Secondary Roads Department provided a fully loaded (51,560 lb.) tandem axle dump truck which was used for load testing. Four load cases (Figure 18) were investigated and two sets for each case were performed.

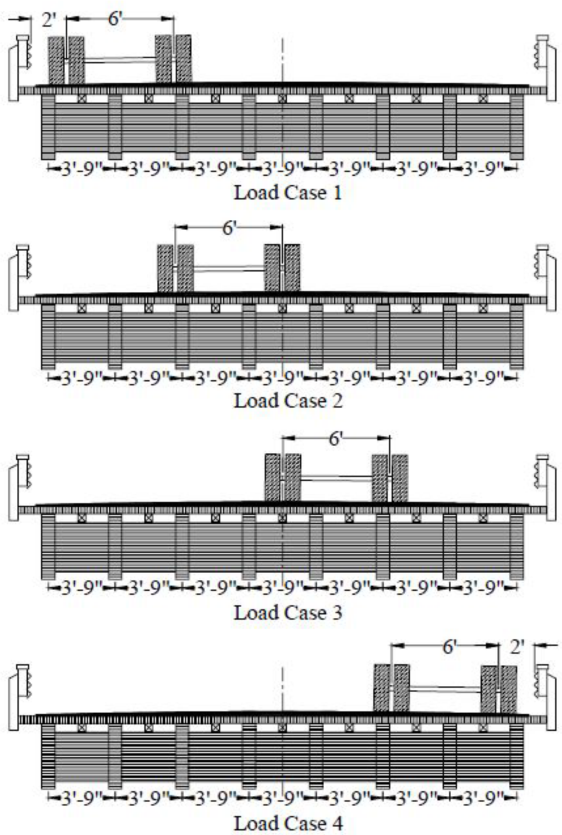


Figure 18: Load cases for Delaware county bridge [36].

The overall bridge performance was adequate and within the limit for static load testing. The global deflection of the bridge was within AASHTO 1996 limits. All girders performed as intended and the girder ends showed good bearing during the tests. Girder G1, which was damaged prior to testing, showed no noticeable stiffness reduction. As of a 2006 (2 years after construction) inspection, all the girders were in good condition and the FRP/timber bonds showed no signs of deterioration.

4.2 Pile Applications

This section briefly discusses FRP repair of biologically deteriorated timber piles and an evaluation of FRP repaired wood piles subjected to a bending test.

4.2.1 Deteriorated timber pile rehabilitation, Louisiana

The Southern Plains Transportation Center sponsored a program to evaluate the capacity of deteriorated timber piles strengthened with FRP under concentric and eccentric loads with different deterioration configurations [37]. The timber piles of Louisiana bridges are experiencing biological degradation in the wet-dry zone. An example of a biologically degraded pile is shown in Figure 19. Since complete replacement of the piles is not economically feasible, in situ repair of the piles with FRP was explored, which eliminates the need for shoring the superstructure and road closure.

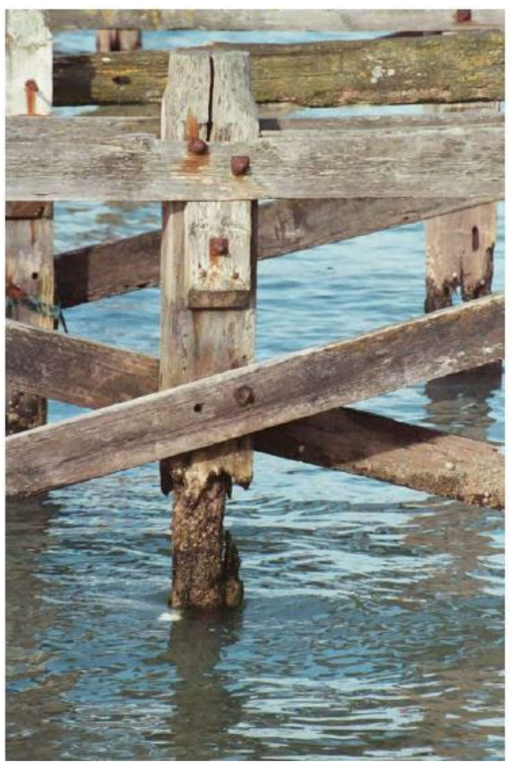


Figure 19: Biologically degraded pile [37].

In this study, the observed damaged condition in the wet-dry zone was mimicked. An hourglass shaped reduction of the cross-sectional area was implemented using a table saw and five different damage types were introduced for the test program (Figure 20). The test program consists of a total 42 monotonic tests, with 21 tests on concentrically loaded piles and 21 tests on eccentrically loaded piles (Figure 21). A self-contained loading frame was used to test all piles, with a capacity of 400 kips. Linear variable differential transducers (LVDTs) were used at the top and bottom of the piles to measure the axial deformation. The aim of these tests was to assess the efficiency of different repair techniques in restoring the original capacity of the piles. Three different commercially available repair techniques from three different companies (Denso North America, Simpson Strong Tie, and Pilemedic) were investigated in this study (Figure 22).

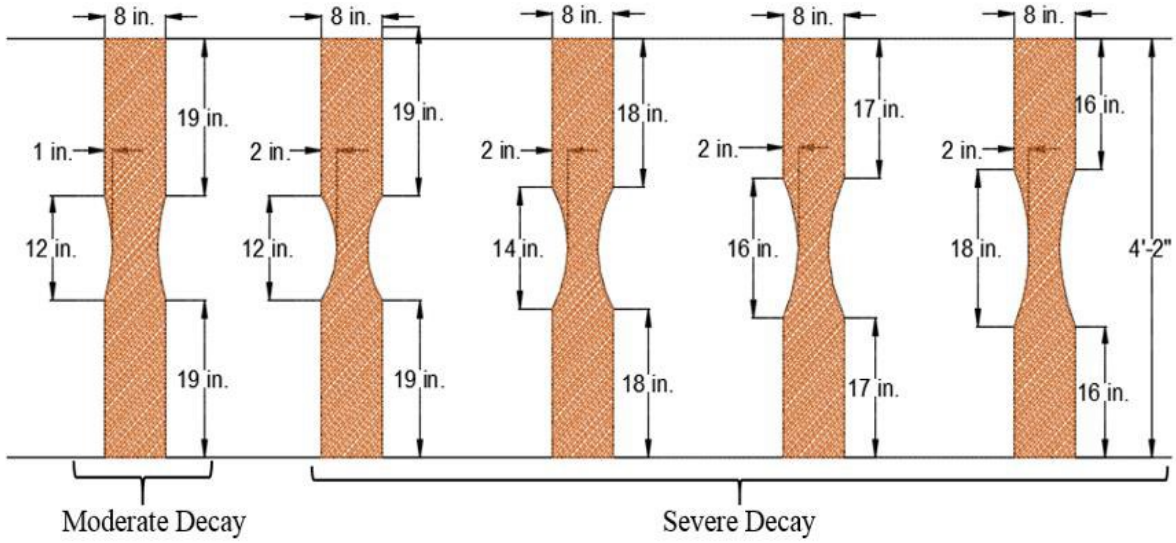
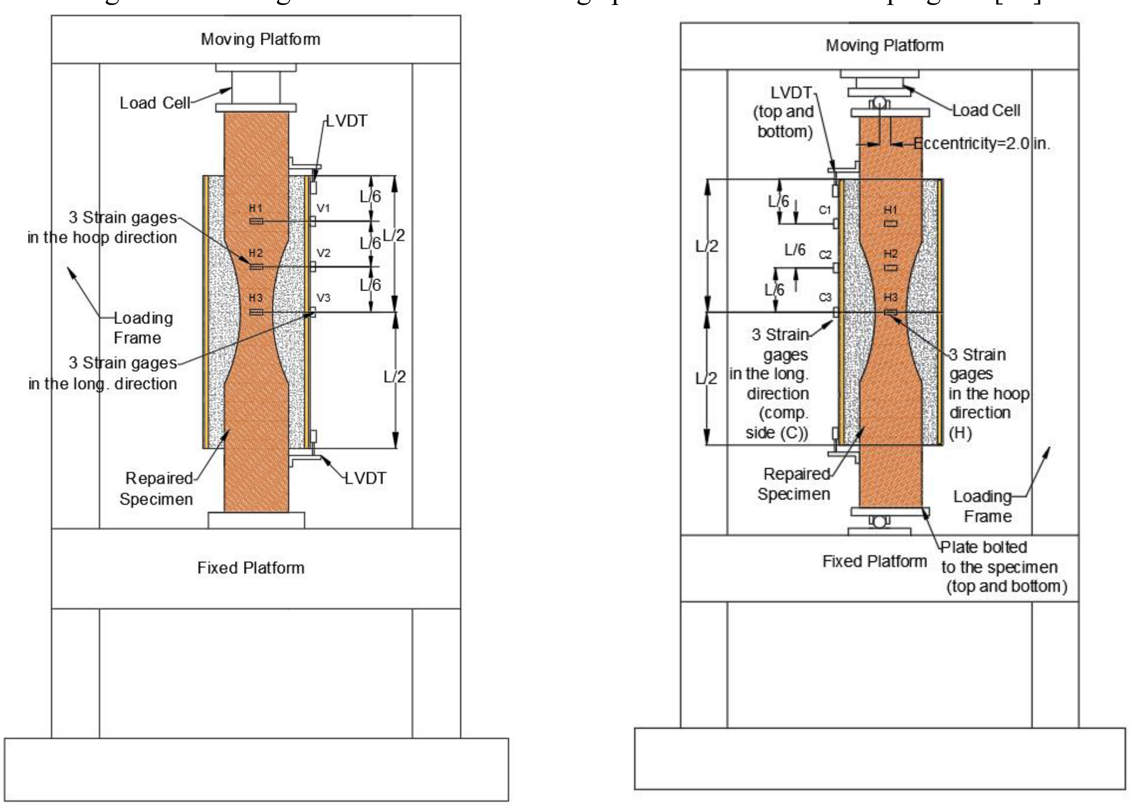


Figure 20: Configuration of induced damage piles for Louisiana test program [37].



(a) Concentrically loaded.

(b) Eccentrically loaded.

Figure 21: Test setup for Louisiana test program [37].

(a) Denso (b) Simpson Strong Tie (c) Pilemedic

Figure 22: Repaired timber piles for Louisiana test program [37].

All repaired piles exhibited higher concentric load carrying capacities than the damaged piles and surpassed the axial capacity of the reference undamaged pile. Both the concentric and eccentric load carrying capacities of the damaged piles increased significantly after repairing them with FRP composites, regardless of the repair technique. No slip was observed at the pile-fill interface during the testing. They concluded that all investigated repair techniques are efficient and can be used to restore the capacity of damaged timber piles.

4.2.2 FRP repaired wood pile evaluation under bending tests, University of Maine

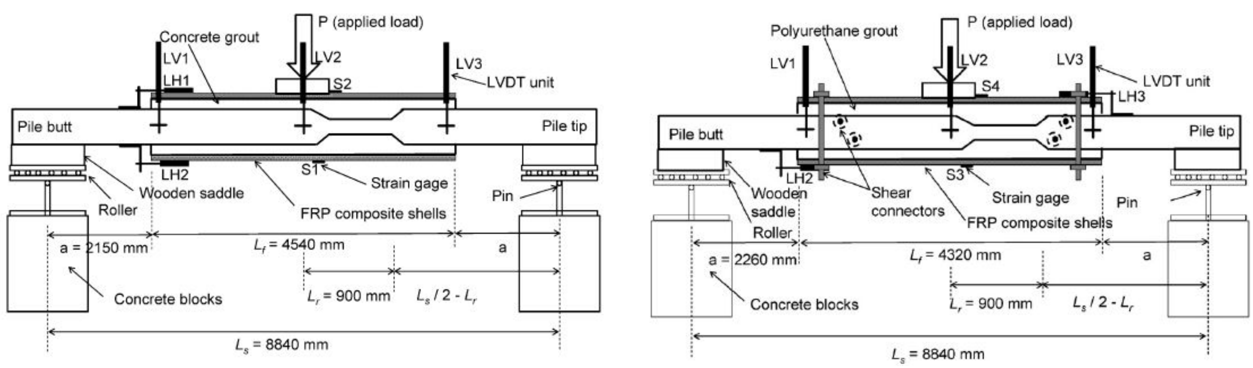
Wood piles in the marine area deteriorate from marine borers, crustaceans, fungi, and other sources, causing them to lose capacity [38], and therefore require restoration to regain strength. This project focused on repairing pre-damaged wood piles with a specially developed FRP composite shield and investigated their responses in bending.

Southern yellow pine class B wood piles were selected as test specimens (details listed in Table 5). The damaged piles were achieved by reducing approximately 62% of the diameter of the cross-section over a segment of 35.4 inches (900 mm) from the center span toward the pile tip. Then unidirectional woven E-glass fabric with an underwater curing epoxy adhesive, named Hydrobond 500 were selected as the reinforcing materials for the two repaired piles. Two types of load-transfer mechanisms were investigated between the wood pile and the FRP composite: (1) cement-based structural grout between the FRP wrap and the wood pile and (2) steel shear connectors with an expanding polyurethane chemical grout between the wood and the FRP wrap.

Table 5: Wood pile systems configuration [38].

System	Wood pile	FRP Composite shield	Grout	Shear connectors	Pile length, L (m)	Span length, L_s (m)
Intact reference (IW)	Intact	N.A.	N.A.	No	9.14	8.84
Damaged control (DW)	Pre-damaged	N.A.	N.A.	No	9.14	8.84
Repair system B	Pre-damaged	Yes	Cement-based	No	9.14	8.84
Repair system C	Pre-damaged	Yes	Poly urethane	Yes	9.14	8.84

The specimens were tested under a three-point bending test procedure (Figure 23). Vertical deflections were measured at mid-span, and the two ends of the FRP composite using LVDTs. Horizontal movement between the wood pile and the FRP composite shield was also measured on the top and bottom at the ends of the FRP composite using LVDTs. Moreover, the load deformation response, strain distribution, ultimate bending moment capacity and failure mode were evaluated.



(a) System B. (b) System C.

Figure 23: Three-point bending test setup for piles [38].

The repaired piles with FRP composite shield and cement-based grout exceeded the bending capacity of the reference wood pile. However, the repair system using the FRP composite shield with steel shear connectors and polyurethane grout did not restore the bending capacity to the capacity of the reference wood pile.

4.3 Pile Cap Applications

This section briefly discusses the investigation of the feasibility of a timber double cap with mechanically fastened FRP strips. Most of the railroad timber bridges in Wisconsin are over 50 years old and are experiencing deterioration due to increased traffic loads. One viable solution to address this problem is to enhance the stiffness of the pile cap and enable better load distribution [22]. The Wisconsin Department of Transportation (WisDOT) sponsored an investigation that focused on exploring mechanically fastened fiber reinforced polymer (MF-FRP) strips fastened to timber with screws to create composite action between two beams. All tests were performed at the Forest Products Laboratory in Madison, WI.

Douglas Fir rough sawn lumber and Douglas Fir creosote treated timber wood specimens were used in this study. The moisture contents of Douglas Fir rough sawn lumber range from 9% to 13% and their grading was Select Structural. The grade of Douglas Fir creosote treated timbers was Grade No. 1. The composite material used in this study was SAFSTRIP manufactured by Strongwell. SAFSTRIP (Figure 24) consists of carbon tows surrounded by layers of glass fiber mats, impregnated with a vinyl ester resin, and has dimensions of 4 inches (102 mm) wide and 0.13 inch (3.2 mm) thick. The design tensile strength and modulus are 92.9 ksi and 9020 ksi, respectively.

Figure 24: SAFSTRIP [22].

In this study, several test series were conducted, including deep beams over short spans and full-scale specimens, to determine if and how FRP strips improved the member's performance. Tests were conducted over various widths of beams and lengths of spans to investigate how the geometry affected the strengthening's ability to create composite action. The testing for this project was divided into two phases. For phase 1, beams were tested over two span lengths (126 inches and 60 inches) and there were two series of testing beams: width series and depth series. Four strengthening configurations were explored for the width series beams (Table 6) and five strengthening configurations were tested for depth series beams (Table 7). This phase's objectives were (1) to investigate the influence of beam width and depth on the composite behavior of MF-FRP and (2) to assess the impact of the distance between supports. The test setup for Phase 1 was a typical three-point bending test for wood specimens (Figure 25). LVDTs were used to collect deflection data, and strain gauges were utilized on the FRP. Data was collected using LabView.

Table 6: Phase 1 - width series beam configuration [22].

Beam Width	Beam Depth	Configuration	Description
4" 8" and 12"	4"	Single Beam	A single member
4" 8" and 12"	4"	Stacked Beams	One beam on top of the other – no composite action
4" 8" and 12"	4"	Epoxied Beams	Simulates fully composite section between two members
4" 8" and 12"	4"	FRP X-Braced Beams	FRP fastened to outer surface on either side, achieving some composite action

Table 7: Phase 1 - Depth series beam configuration [22].

Beam Width	Beam Depth	Configuration	Description
4"	14"	Single Beam	A single member
4"	14"	Stacked Beams	One beam on top of the other – no composite action
4"	14"	Epoxied Beams	Simulates fully composite section between two members
4"	14"	FRP V-Braced Beams	FRP fastened to outer surface on either side, achieving some composite action
4"	14"	FRP X-Braced Beams	FRP fastened to outer surface on either side, achieving some composite action

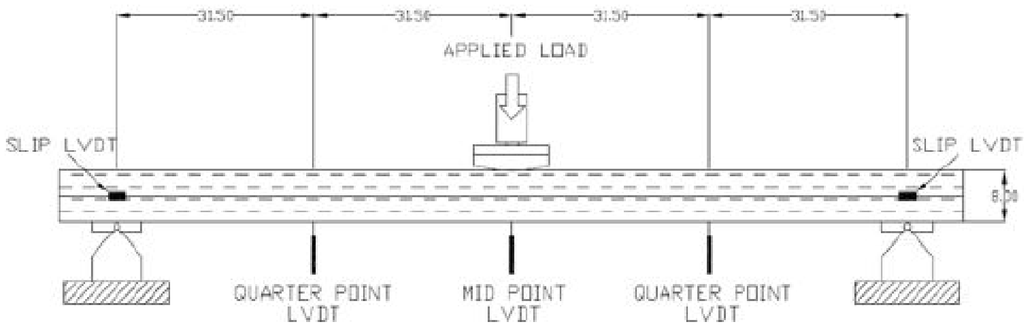


Figure 25: Test setup of Phase 1 [22].

Phase 2 tests were conducted on full-sized specimens provided by Wisconsin & Southern Railroad (WSOR), which were typical of the in-situ condition of a timber railroad bridge. Five supports were used to replicate the support condition of the piles. Static testing was completed on various MF-FRP configurations (Table 8), and then one configuration was subjected to 1 million cycles of dynamic testing. The objectives of this phase were (1) to determine the applicability of the MF-FRP method in continuous deep beams over multiple short spans, (2) to investigate the potential of MF-FRP strips in redistributing loads, and (3) to examine the behavior of the beam and determine whether it acts in accordance with design equations. A custom designed test setup (Figure 26) was used for phase 2 testing, with unique parts designed to fit the existing test area at the Forest Products Lab. Cyclic loading was set at 0.75 cycles per second, and the load varied between approximately 8 kips and 45 kips during each cycle. LVDTs were used to measure deflections, and strain gauges were placed on the FRP. All data was collected using LabView.

Table 8: Phase 2 beam configuration [22].

Specimen Name	Description	Test Load (lbs)
Prescribed Spacing 33" – 30" – 30" – 33"		
NB12-1	Single pile cap	30,000
NB12-2	Single pile cap	30,000
NB12-3	Single pile cap	30,000
NB12-4	Single pile cap	30,000
NB12-2 over NB12-1	Double pile cap	40,000
NB12-3 over NB12-2	Double pile cap	40,000
NB12-3 over NB12-4	Double pile cap	40,000
Worst Spacing 27" – 36" – 36" – 27"		
NB12-3 over NB12-4	Double pile cap	40,000
NB12-2 over NB12-3	Double pile cap	40,000
NB12-1 over NB12-4	Double pile cap	40,000
NB12-1 over NB12-4 FRP	Double pile cap with MF-FRP strips in various configurations	40,000
NB12-2 over NB12-3 FRP	Double pile cap with MF-FRP strips in various configurations	40,000 and 150,000

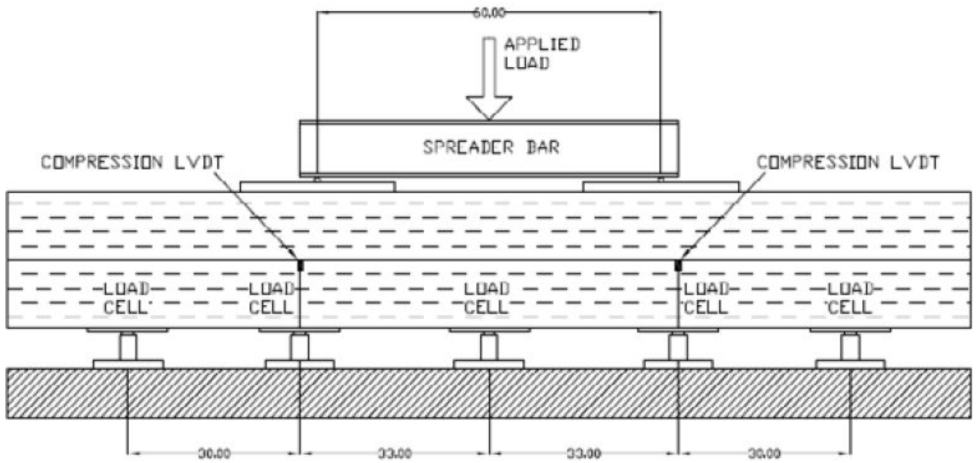


Figure 26: Test setup of Phase 2 [22].

One main finding from this study was that composite action between two timber members can be achieved with mechanically fastened FRP strips, and this method showed great potential for creating composite, stiffer double pile caps. MF-FRP strips also increase the flexural stiffness of timber beams in bending with large span-to-depth ratios. However, MF-FRP strips did not significantly improve load distributions to piles.

5. RC BRIDGE REPAIR WITH FRP

The RC (Reinforced Concrete) bridge repair with FRP section summarizes the application of FRP in RC bridge projects. Specifically, this section discusses the FRP repair of several RC bridge elements including girders, piles/columns, and pier caps.

5.1 Girder Applications

This section summarizes three RC bridge girder FRP repair/strengthening including Louisa-Fort Gay bridge, Kentucky, Uphapee Creek bridge, Alabama, and Route 378 Bridge, New York.

5.1.1 Retrofit of the Louisa-Fort Gay bridge, Kentucky

The Louisa-Fort Gay is a 12-span continuous bridge structure consisting of composite concrete deck-steel girder span and reinforced concrete middle span and is located in Lawrence County, Kentucky. Flexural cracks (Figure 27) were found in the positive bending regions of the bridge girders because of excess traffic loading that exceeded the legal weight limit specified by the American Association of State and Highway Transportation Officials (AASHTO) [39].

Figure 27: Cracks in Louisa Fort Gay bridge [39].

FHWA and the Kentucky Transportation Cabinet sponsored a program to repair and strengthen the bridge. CFRP laminates were selected as the strengthening material (Figure 28). Before applying the CFRP laminates, surface preparation was performed, including cleaning, and removing loose concrete particles, debris, and other contaminants. The CFRP laminate application process included applying the epoxy on the concrete surface, placing the laminates to the structure surface, pressing the laminates, and removing excess adhesives.

Figure 28: Repaired Louisa Fort Gay bridge girders [39].

For the post monitoring of the bridge performance, crack gauges were installed during the strengthening process. After 3 years of monitoring, no cracks were recorded.

5.1.2 Repair of the Uphapee Creek bridge, Alabama

The Uphapee Creek, three span, continuous bridge was identified insufficient to carry modern traffic loads. To strengthen the bridge, the Auburn University Highway Research Center conducted a study that was sponsored by the Alabama Department of Transportation (ALDOT) and FHWA. The bridge was designed following the H-15 traffic loading, but the minimum design specification required AASHTO HS 20-44 for the bridges carrying heavy traffic loading. Significant flexural cracks were also identified in the positive moment regions of the bridge girders [40].

The Tyfo UC Composite Laminate Strip System from Fyfe Company, LLC was selected as the strengthening material (Table 9). Tyfo TC epoxy was used as the adhesive, primed with Tyfo S Epoxy. The strengthening process included surface preparation, epoxy injection to the cracks, epoxy application to the structure surface, and placing the FRP to the surface (Figure 29). Figure 30 shows the strengthened girders.

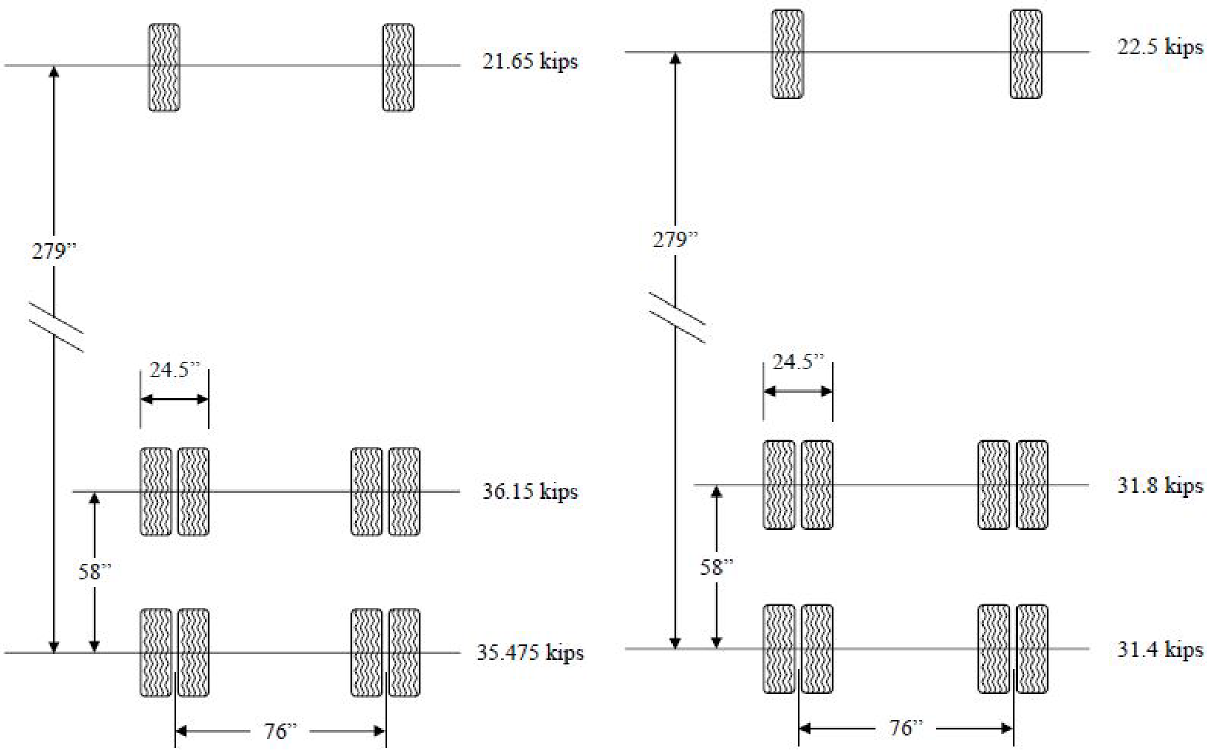
Table 9: Tyfo UC composite laminate properties [40].

Property	Nominal Value
Ultimate tensile strength in primary fiber direction	405,000 psi
Ultimate tensile strength 90° to primary fiber direction	0 psi
Tensile Modulus	22.5 x 10^6 psi

Figure 29: Application of FRP strip to the Uphapee Creek bridge girder [40].

Figure 30: FRP-strengthened Uphapee Creek bridge girders [40].

Static and dynamic tests were performed before and after the FRP composite installation. Field live load tests were performed with two identical load test trucks (LC-5 and LC-6, Figure 31) owned and operated by ALDOT. Electrical resistance strain gauges (ERSGs) and deflectometers were used to measure live load deflections. MEGADAC 3415AC high-speed data acquisition system, manufactured by OPTIM Electronics, was employed for data acquisition.



(a) LC-5. (b) LC-6.

Figure 31: Truck configuration for Uphapee Creek bridge field test [40].

In conclusion, the strengthened girders performed as predicted. No major problems were found in post monitoring after 6 months. A tap test was also performed, and no delamination was found in the FRP bond. It was also mentioned that road closures were not required while applying the externally bonded FRP strengthening techniques.

5.1.3 Repair of Route 378 Bridge, New York

A 40-ft (12.19 m) long bridge carries State Route 378, located in the City of South Troy, Rensselaer County, New York. During a routine inspection, freeze-thaw cracking, concrete delamination, and efflorescence were found at several locations of the bridge beams [41]. The New York State Department of Transportation (NYSDOT) decided to repair the bridge with FRP laminates. Replark 30 unidirectional carbon fiber was selected as the strengthening material, which was manufactured by Mitsubishi Chemical Corporation in Japan. The surface was cleaned, and the loose concrete was removed. Cement-based grout material was injected into the cracks, and then the surface was smoothed by sandblasting. The laminates were placed on the structure surface after applying epoxy. After drying, the structure was repainted to match the original structure (Figure 32). Load testing was done before and after strengthening the bridge girder with a 44-kip

(196 kN) truck (Figure 33). Conventional strain gauges were used to measure the deflection, which were manufactured by Measurements Group, Raleigh, North Carolina.

Figure 32: FRP-strengthened girder of State Route 378 bridge, New York [41].

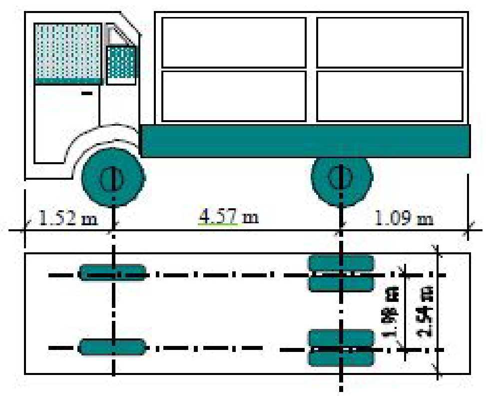


Figure 33: Load truck configuration for field test of State Route 378 bridge, New York [41].

The load distribution to bridge beam was improved with the girder repairing. It was also discussed that the rehabilitation process was cost effective since road closure was minimal.

5.2 Pile/Column Applications

This section briefly discusses FRP-repair of corrosion damaged RC bridge columns in Michigan and FRP-repair of corrosion damaged submerged concrete piles of the Friendship trail bridge, Florida.

5.2.1 Repair of corrosion damaged columns, Michigan

Chloride contamination has significantly damaged numerous bridge columns in Michigan, such as corrosion of the steel reinforcement and swelling and spalling of the concrete [42]. The Michigan Department of Transportation (MDOT) sponsored a program to investigate the effectiveness of FRP wrap to address the problem. Michigan State University (MSU) conducted several tests to explore freeze-thaw durability of FRP-wrapped specimen subjected to an internal expansive force, the effect of wrapping on the rate of corrosion, the impact resistance of FRP, and the effect of elevated temperature on wraps. MSU fabricated a 4-ply composite Tyfo-S fiber glass/epoxy sheet and a 2-ply Tonen carbon/epoxy sheet which were used for all lab testing. Lab testing results indicated that freeze-thaw cycles did not significantly impact the compressive strength of glass and carbon fiber, and both fibers effectively slowed down the corrosion rate. Carbon and glass fiber performed well during the impact test. However, the epoxy in the FRP deteriorated when exposed to temperatures exceeding 200°C, resulting in the ineffectiveness of the FRP.

The next phase of the program was the field application of the strengthening technique. Six columns were selected for this program which were located under the I-96 overpass, Lansing, Michigan. The columns had surface spalling and exposed rebar at several locations (Figure 34). The strengthening configurations were: two reference columns, two columns wrapped with two layers of carbon fiber, and two columns wrapped with three layers of glass fiber. Figure 35 shows one of the repaired columns.

Figure 34: Deteriorated column of I-96 overpass bridge, Michigan [42].

Figure 35: Repaired I-96 overpass bridge columns [42].

The repaired columns were monitored twice a month for 10 months. There were some drifts in the post monitoring readings, but no significant problems were found.

5.2.2 Corrosion repair of submerged concrete piles of Friendship trail bridge, Florida

High concentrations of chloride ions in seawater causes severe corrosion damage to the submerged concrete piles [43]. Additionally, the wet/dry cycles and high humidity can deteriorate concrete structures rapidly. To address this problem, this project investigated FRP repairing techniques for several corrosion-damaged underwater concrete piles. The 2.6-mile-long Friendship trail bridge is located in Tampa Bay, Florida, and was selected for the project. Two types of FRP strengthening systems were introduced in the study: 1) Aquawrap, a uni-directional/bi-directional carbon FRP repair system with water-activated urethane resin, and 2) Tyfo SEH-51, a weave, uni-directional glass fabric with Tyfo-S underwater epoxy. A total of eight piles were selected for the study (Table 10). A pressure washer was used to remove all the dust and loose concrete from the pile surface above the water. A quick-setting hydraulic cement was injected into the cracks and any discontinuities. Four piles were wrapped following the wet lay-up process, and the other four piles were wrapped following the prepreg system. A boat was used to wrap the piles above water, and divers wrapped the piles under water, shown in Figure 36. A scaffolding system was also introduced to have easy access to the pile.

Table 10: Pile configuration of Friendship trail bridge project [43].

Pier number	Repair system	Specimen type	Pile name	Instrumentation
Pier 99	None	Control	99-N	Yes
	None	Control	99-S	Yes
Pier 100	Aquawrap®	Carbon 1 + 2 layers[a]	100-N	Yes
		Carbon 1 + 2 layers	100-N*	No
		Glass 2 + 4 layers	100-S*	No
		Glass 2 + 4 layers	100-S	Yes
Pier 101	Tyfo® SEH-51A	Glass 2 + 4 layers	101-N	Yes
	Tyfo Zinc Cathodic Protection	Glass 2 + 4 layers	101-S	Yes

(a) Using a boat.

(b) Using divers.

Figure 36: FRP wrapping of Friendship trail bridge pile [43].

It was concluded that the prepreg system was more convenient than the wet lay-up process. However, the wet lay-up system performed better. Bond tests were also performed after two years of repair. The repaired piles performed as intended during the post-monitoring.

5.3 Pile Cap Applications

This section discusses the FRP jacket repair deteriorating pier caps of Silver Spring Cove Bridge, Rhode Island using the vacuum bagging process and the FRP-repair of the Morganza Spillway bridge pile cap located in Louisiana.

5.3.1 FRP jackets for deteriorating pier cap of Silver Spring Cove Bridge, Rhode Island

The Rhode Island Department of Transportation sponsored a program to repair the deteriorating RC pier cap of the Salt Pond Road bridge in South Kingstown, Rhode Island. The pier caps showed severe spalling and cracking, and the reinforcements were exposed at several locations [44] (Figure 37). The bridge is located near the ocean, and the constant exposure to contaminated water flowing over the pier caps was identified as the cause of the severe deterioration.

Figure 37: Deteriorated pier cap of Salt Pond Road Bridge [44].

The vacuum-assisted impregnation technique, commonly known as "vacuum bagging" in the aerospace industry, was employed to fabricate a composite jacket for repairing the pier caps and prevent further deterioration. E-glass fiber from the Saint Gobain Company was chosen for the strengthening material. This specific fabric was selected due to its lightweight and high tensile and flexural strength properties. A low-viscosity resin was necessary for this application technique to flow better. Pot life was also critical since this process required time to vacuum. Three epoxy resins were selected: Tyfo S, Sikadur Hex 300, and Sikadur 35. A rotary vane high vacuum pump with a 0.5 horsepower capacity was selected, which ran at a speed of 1725 RPM with a frequency of 60 Hz.

Before field application, Rutgers University in New Jersey performed lab tests on full-scale specimens to ensure the feasibility of the repairing techniques. The testing procedure includes cleaning the concrete surface with a pressure washer to remove all loose debris, applying a thin layer of epoxy resin, impregnating E-glass fiber with resin on top, placing the wet fabric on the structure surface, attaching the vacuum bag, and running it for 4 hours. The lab test went well, and it was concluded that the resin system and vacuum bagging were feasible for the actual application.

The faculty and students at Rutgers University and the University of Rhode Island carried out the field application with the help of professional staff. Scaffolding and surface preparation were complete before the actual application (Figure 38). E-glass fabric with Sikadur Hex 300 resin was selected as the strengthening material for field application. After the concrete surface was completely dry, the FRP composite was placed. The vacuum bagging process (Figure 39) began after 16 hours of placing the FRP.

Figure 38: Scaffolding and safety measures for repairing the Salt Pond Road Bridge [44].

Figure 39: Vacuum bagging system adopted in repairing the Salt Pond Road Bridge [44].

The post-monitoring of the repaired bridge included visual inspection, chloride level tests, and compressive strength tests of the repaired pier cap. The repaired area performed as intended, and the compressive strengths were higher than the design strength.

5.3.2 FRP-repair of the Morganza Spillway bridge pile cap, Louisiana

The pile cap of the Morganza Spillway bridge in Louisiana needed repairing, as the previous repair method of patching the damaged area with structural grade high-adhesive material epoxy concrete was ineffective and resulted in delamination (Figure 40) [45]. The Louisiana Department of Transportation and Development sponsored a program to repair the damaged pile cap and Louisiana State University conducted the project. CFRP was used as the strengthening material, with Young's modulus of 90 million psi. After placing the FRP on the concrete surface, the bent surface was coated with an inorganic polymer coating reinforced with short carbon fiber (Figure 41). The coating formulation, originally developed for use in aircraft structures, was used to prevent deterioration and provide UV-protection, and had self-cleaning properties.

Figure 40: Delamination under the bearing plate of the Morganza Spillway bridge, Louisiana [45].

Figure 41: Repaired pile cap of the Morganza Spillway bridge, Louisiana [45].

No significant problems were found during the two years of monitoring and the repair zone of the pile cap performed as intended.

6. MDT BRIDGE REPAIR WITH FRP

This section briefly discusses the Montana bridge projects in which FRP has already been used to repair and strengthen different bridge elements. Table 11 provides a brief overview of these projects.

According to an extensive search through MDT's bridge inventory database [46], nine reinforced concrete bridges have been repaired in Montana using FRP wrap. The repairs include two girder repairs, six cap repairs, one pile repair, and four column repairs. According to the most recent inspection, the FRP repaired bridges #01044, #01490, #01491, #05868, #05972, and #07011 were in good condition. However, bridge #02096 showed some random delamination in the FRP repair area.

Table 11: FRP-repaired reinforced concrete bridges in Montana.

MDT Bridge Number	Construction Year	Location	Repairing Year	Repaired Area	Last Inspection Year
#01044	1965	8M N Clark Canyon Dam, Beaverhead, Butte	2021	Girder, Span 1.	2021
- As of 2021, FRP repairing was in good condition.					
#01490	1979	1.2M S Garrison, Powell, Butte	2003	Top portion of cap, Bent 2 and 3.	2022
- As of 2020 inspection, the concrete caps with a FRP wrap are in good condition.					
#01491	1979	1.2M S Garrison, Powell, Butte	2003	Top portion of cap, Bent 2 and 3.	2022
- As of 2022, FRP wrap are in good condition.					
#02096	1964	0.6M W Butte, Silver Bow, Butte	2020	Cap faces and Column.	2022
- Cap faces and column wrapped with FRP. - In 2022 inspection, some random delamination at spalls in column in FRP repair were observed.					
#05868	1960	16M NE Wisdom, Deer Lodge, Butte	2020	Cap.	2022
- In 2020 the concrete caps were wrapped with a fiber reinforced polymer cap repair. - No significant defects noted in 2022.					
#05972	1971	1M N Hobson, Judith Basin, Billings	2021	4 inside girders at abutment 4.	2023
- No defects noted on the girders in 2023 inspection.					
#06860	1972	Columbia Falls, Flathead, Missoula	---	Column cap.	2022
- Bent 3 column cap repair with epoxy impregnated FRP wrap.					
#06982	1936	Havre- 7th Ave N, Hill, Great Falls	2021	Caps at Bent 15, 16, and 21.	2022
- As of 2016 inspection, bent 15, 16, and 21 showed some cracks and spalls. - The caps at Bents 15, 16, and 21 were repaired with epoxy wraps and the piles were FRP jacketed.					
#07011	1962	Missoula-S Higgins Ave, Missoula	2022	Bent 2, Column 2, full height FRP wrap. Bent 3, Column 2, 3.5 ft (1.1 m) high FRP wrap at the top of the column.	2022
- No visible delamination found in 2022 inspection.					

A thorough search of the same database [46], revealed that FRP has been more extensively applied to timber bridges in Montana, with jacket repairs made to piles on 56 bridges. The FRP wrap was applied to piles at various heights as needed. Appendix A: FRP-repaired timber bridges in Montana presents a detailed summary table of all FRP-repaired timber bridges located in Montana. Most repairs were made between 2020-2021 and were inspected one year later. As of the most recent inspection, no deterioration/damage has been reported for most of the bridges and they were performing as expected.

7. SUMMARY AND FUTURE DIRECTION

Overall, FRP has been successfully implemented in various projects worldwide to strengthen and repair bridge elements and the use of the material has increased over time. This report provided an overview of different techniques for applying FRP in strengthening and repairing structures, including external wrapping, NSM bars, laminates, and FRP strips. Additionally, selected uses of FRP to repair girders, piles, and pile caps in timber and RC bridge projects were summarized. Overall, using FRP in timber and RC bridge projects has shown promising results in strengthening and restoring structural capacities and post-monitoring results have demonstrated successful restoration and improved performance of the repaired bridge components.

FRP wrap has already been used to repair and strengthen RC and timber bridges in Montana. Various elements of nine RC Montana bridges have undergone FRP repairs, including girder, cap, pile, and column repairs. Recent inspections have shown that most FRP-repaired RC bridges are in good condition, except one bridge that exhibited random delamination in the repair area. FRP wrap has been used to jacket several timber piles of 56 Montana bridges and no significant damage has been found in the post-inspections.

In addition to the existing Montana bridge repairs with FRP that have been discussed, the database was used to search for any MDT bridges that have been identified (by MDT) for potential repair with FRP. Table 12 summarizes the findings from this search and these bridges could be potential options for the implementation phase of the current research, depending on the needs of MDT.

Table 12: Potential RC and timber bridges for FRP repair(s) in Montana.

MDT Bridge Number	Construction Year	Location	Construction Material	Possible Repair Area/Inspection Comments	Recent Inspection Year
#01166	1969	1.2M S Clancy, Jefferson, Butte	RC	Crack Seal, Class A Repair, Possible FRP Reinforcement.	2022
#01167	1969	0.6M S Clancy, Jefferson, Butte	RC	Crack Seal, Class A Repair, Possible FRP Reinforcement.	2022
#02625	1979	19M W Glendive, Dawson, Glendive	Timber	Abutment 1 Pile 4, Abutment 3 Pile 4 FRP wrap due to moderate to severe internal decay.	2022
#03202	1931	7M W Whitehall, Jefferson, Butte	Timber	Recommend jacketing or replacing abutment 1 Pile 3 due to decay	2022
#03728	1947	3M W Huson, Missoula, Missoula	Timber	Recommend repairing or retrofitting intermediate timber caps on Bents 8, 9, and 10.	2022
#04298	1930	7M E Rosebud, Rosebud, Glendive	Timber	Repair recommendation: As of 2020, Jacket repair Bent 3, Pile 2 As of 2022, Jacket repair Bent 3 Pile 6 As of 2022, Repair split in girder S5G2	2022
#04536	1937	6M NW Greycliff, Sweet Grass, Billings	Timber	Repair the split at Span 1 Girder 11	2021

Overall, this report is intended to inform the MDT Technical Panel on other state projects using FRP composites in various forms to repair/strengthen RC and timber bridge elements. Critical findings, including surface preparation techniques, application methods, and performance were discussed. This information will be used as a baseline to facilitate further discussion during the Intermediate Technical Panel Meeting and inform the decision on which application(s) will be pursued for the remaining duration of this project.

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Appendix A: FRP-repaired timber bridges in Montana

MDT Bridge Number	Construction Year	Location	Repairing Year	Repaired Area	Last Inspection Year
#02526	1934	4M W SIMMS, Cascade, Great Falls	2021	Bent 2: Pile 4.	2022
- Bent 2 Pile 4 was jacketed with FRP wrap from ground line to 2 ft (0.61 m) up.					
#02568	1928	19M NE Miles City, Custer, Glendive	2020	Bent 2: Piles 4 and 5.	2022
- No crushing or distortion was noted in 2022 inspection					
#02569	1929	20M NE Miles City, Custer, Glendive	2020	Bent 2: Pile 4.	2022
- No decay was found in 2022 inspection.					
#03201	1931	4M W Whitehall, Jefferson, Butte	2020	Bent 2: Pile 6. Bent 3: Pile 1.	2022
- Bent 2 Pile 6 and Bent 3 Pile 1 were wrapped with FRP for the full pile height.					
#03202	1931	7M W Whitehall, Jefferson, Butte	2021	Bent 2: Pile 2, 3.	2022
- Bent 2 piles 2 and 3 were FRP wrapped.					
#03344	1933	1M NE Wolf Creek, Lewis and Clark, Great Falls	2021	Abutment 1: Pile 5. Abutment 2: Pile 2.	2022
- FRP wrap repair required due to decay.					
#03345	1933	2M NE Wolf Creek, Lewis and Clark, Great Falls	2021	Abutment 1: Pile 5. Abutment 2: Pile 1.	2022
- FRP wrap was applied over the full exposed heights of the piles due to decay.					
#03347	1933	5M NE Wolf Creek, Lewis and Clark, Great Falls	2021	Abutment 2: Pile 1, 3.	2022
- A2P1 and A2P3 were wrapped with FRP from the ground line to 3 ft (0.91 m) and 1.8 ft (0.55 m) above ground, respectively.					
#03728	1947	3M W Huson, Missoula	2017	Bent 6: Pile 1. Bent 8: Pile 3. Bent 12: Pile 4.	2022
- From bent cap down 10 ft (3 m), 6 ft (1.83 m) and 8 ft (2.44 m) FRP wrap was applied to Bent 6, 8, and 12, respectively.					
#04649	1933	10M E Hysham, Tressure, Billings	2018	Bent 2: Pile 3. Bent 3: Piles 1-4.	2021
- The repair was in good condition as of 2021 inspection					
#04862	1947	2M W Huntley, Yellowstone, Billings	2020	Bent 3: Piles 1, 2, and 8. Bent 4: Pile 8.	2022
- The piles were FRP jacketed.					
#05070	1942	Chinook, Blaine, Great Falls	2021	Abutment 1: Piles 1, 2. Bent 2: Pile 7.	2021
- The piles were RFP wrapped at full height. - No defects were found in 2021 inspection.					
#05072	1942	1M E Chinook, Blaine, Great Falls	2021	Bent 2: Pile 5. Bent 3: Pile 5.	2021
- The piles were RFP wrapped.					
#05081	1940	Zurich, Blaine, Great Falls	2021	Abutment 4: Pile 3. Bent 2: Pile 5.	2021
- The piles were RFP wrapped.					
#05170	1940	2M NE Sun River, Cascade, Great Falls	2021	Bent 3: P2.	2022
- Bent 3 Pile 2 was jacketed with an FRP wrap from ground line up to 4.9 ft (1.5 m) due to decay at the ground line.					
#05246	1933	5M S Ronan, Lake, Missoula	2021	Bent 1: pile 4 and 5. Bent 2: pile 1 and 2. Bent 4: pile 4.	2023
- The piles were FRP wrapped. - No visible sign of deterioration.					

#05445	1935	1M E Lavina, Golden Valley, Billings	2020	Bent 2: Pile 4. Bent 3: Pile 3.	2022
#05493	1947	3M W Sumatra, Rosebud, Billings	2022	Abutment 3: Pile 4.	2022
- Abutment 3 Pile 4 was FRP Jacketed.					
#05496	1947	Ingomar, Rosebud, Billings	2020	Abutment 1: Pile 5. Abutment 2: Pile 4.	2022
- The piles were RFP wrapped.					
#05498	1941	32M NW Forsyth, Rosebud, Glendive	2022	Abutment 3: Pile 5.	2022
- The pile was RFP wrapped.					
#05690	1941	11M NE Ekalaka, Carter, Glendive	2022	Abutment 1: Pile 5. Bent 2: Pile 1.	2022
- Abutment 1, Pile 5 and Bent 2, Pile 1 were treated with FRP wrap and epoxy injection. - No significant defects noted in 2022 inspection.					
#05726	1931	7M E Pipestone Pass, Jefferson, Butte	2021	Bent 3: Pile 6. Bent 5: Pile 5.	2022
- The pile was RFP wrapped.					
#05735	1939	15M S Opheim, Valley, Glendive	2022	Abutment 1: Piles 1 and 2.	2022
- Abutment 1 Piles 1 and 2 were treated with FRP pile wraps. - Piles were functioning as intended and no defects were noted in 2022 inspection.					
#05807	1936	13M NW Avon, Powell, Butte	2019	Bent 2: Piles 4, 5, and 7. Bent 3: Piles 4 and 5.	2021
- The piles were repaired with fiber reinforced polymer. - The repair appears to be functioning as intended in 2021 inspection.					
#05811	1965	4M SE Helmsville, Powell, Great Falls	2021	Abutment 1: Pile 3, 5. Abutment 2: Pile 7.	2021
- The piles were RFP jacketed.					
#05812	1965	2M SE Helmsville, Powell, Great Falls	2021	Abutment 1: Pile 6.	2021
- The pile was RFP jacketed 3 ft (0.91 m) above groundline.					
#05850	1942	14M S Harlowton, Wheatland, Billings	2020	Abutment 1: Piles 1 and 2.	2022
- The piles were FRP jacketed.					
#05942	1953	9M SW Whitehall, Jefferson, Butte	2022	Abutment 1: Piles 2-6. Bent 2: Pile 5. Abutment 3: Pile 4.	2022
- The piles were FRP wrapped.					
#05995	1939	7M NW Grass Range, Fergus, Billings	2021	Bent 2: Pile 4.	2022
- The pile was jacketed with FRP.					
#05998	1939	4M NW Grass Range, Fergus, Billings	2020	Bent 3: Piles 4 and 5.	2022
- The piles were jacketed with FRP.					
#06005	1930	8M NE Grass Range, Fergus, Billings	2020	Bent 3: Piles 2 and 4. Bent 4: Pile 1.	2022
- The piles were jacketed with FRP.					
#06078	1955	2M NE White Sulphur Spring, Meagher, Butte	2019	Abutment 1: Piles 1, 6.	2022
- Abutment 1 Piles 1 and 6 were wrapped with FRP. - The FRP jackets were in good condition in 2022 inspection.					
#06131	1940	11M SW Malta, Phillips, Glendive	2021	Bent 4: Pile 1.	2021

-	Bottom 4ft of Bent 4 Pile 1 was FRP repaired.				
#06198	1949	2M SE Geraldine, Chouteau, Great Falls	2019	Bent 2: Piles 3 and 4. Bent 3: Pile 3.	2021
-	The piles had an RFP jacket retrofit around decayed sections.				
#06204	1949	17M S Geraldine, Fergus, Billings	2021	Abutment 11: Pile 6.	2022
-	Abutment 11, Pile 6 was wrapped in FRP.				
#06205	1934	6M NE Stanford, Judith Basin, Billings	2022	Bent 2: Pile 3. Bent 3: Pile 2.	2022
-	The piles were wrapped with FRP.				
#06216	1934	6M W Brooks, Fergus, Billings	2020	Abutment 1: Pile 4.	2022
-	The FRP wrap appears to be functioning as intended in 2022 inspection.				
#06233	1952	9M NE Norris, Madison, Butte	2022	Abutment 1: Pile 3.	2022
-	Abutment 1 Pile 3 was wrapped with FRP over the full exposed height.				
#06264	1951	1M S Lolo Hot Springs, Missoula	2018	Abutment 2: Pile 3.	2022
-	Abutment 2, Pile 3 was wrapped with FRP.				
#06265	1957	Lolo Hot Springs, Missoula	2018	Bent 3: Pile 5. Abutment 4: Piles 1, 2, 4, 5.	2022
-	The piles were wrapped with FRP 2018.				
#06266	1957	Lolo Hot Springs, Missoula	2018	Abutment 1: Piles 4, 6. Bent 2: Pile 5. Bent 3: Pile 4.	2022
-	The piles were wrapped with FRP.				
#06415	1941	13M E Great Falls, Cascade, Great Falls	2021	Pier 2: Pile 1 and 6. Pier 3: Pile 2.	2021
-	Three piles were RFP retrofitted.				
#06460	1936	1M N Saco, Phillips, Glendive	2020	Abutment 1: Pile 1. Bent 2: Pile 2, 3. Abutment 3: Pile 5.	2021
-	All the jacketed piles were functioning as intended in 2021 inspection.				
#06469	1939	Flatwillow, Petroleum, Billings	2020	Abutment 1: Pile 2.	2022
-	Abutment 1, Pile 2 was wrapped in FRP.				
#06471	1948	5M S Winnett, Petroleum, Billings	2022	Abutment 5: Pile 4.	2022
-	The pile was jacketed with FRP.				
#06512	1940	18M NW Terry, Prairie, Glendive	2022	Bent 3: Pile 5.	2022
-	The pile was jacketed with FRP.				
#06548	1947	1M NE Helmville, Powell, Great Falls	2019	Abutment 1: Piles 1-5. Abutment 2: Piles 3 and 4.	2022
-	The piles were wrapped with FRP.				
#06567	1954	2M SE Canyon Creek, Lewis and Clark, Great Falls	2021	Abutment 1: Piles 2 and 5. Abutment 2: Pile 1.	2022
-	The piles were wrapped with FRP due to decay.				
#06571	1949	5M N Canyon Creek, Lewis and Clark, Great Falls	2021	Abutment 1: Piles 1 and 5. Abutment 2: Pile 4.	2023
-	The piles were wrapped with FRP .				
#06574	1949	6M NW Canyon Creek, Lewis and Clark, Great Falls	2019	Bent 2: Pile 1.	2021
-	The pile was wrapped with FRP.				
#06579	1958	3M E Canyon Ferry, Lewis and Clark, Great Falls	2021	Abutment 1: Pile 1. Abutment 2: Pile 1.	2022

- The piles were wrapped with FRP for the full pile height.					
#06606	1959	1M N Shawmut, Wheatland, Billings	2022	Abutment 4: Piles 1 and 3.	2022
- The piles were wrapped with FRP.					
#06682	1964	1M S Glendive, Dawson, Glendive	2022	Bent 2: Pile 6.	2022
- The pile was covered with a FRP wrap retrofit prior to 2022 inspection.					
#06720	1958	Jefferson Island, Madison, Butte	2022	Abutment 1: Pile 4.	2022
- Abutment 1 Pile 4 was wrapped with FRP 4.5 ft (1.37 m) above the groundline.					
#06738	1955	2M S Outlook, Sheridan, Glendive	2019	Abutment 1: Pile 3.	2021
- Abutment 1, Pile 3 previously showed center rot and crushing, was retrofitted with FRP jacket. - No decay was found in 2021 inspection.					
#06895	1960	6M W Billings, Yellowstone, Billings	2021	Abutment 1: Piles 1, 3, 5, 6. Abutment 2: Pile 4.	2022
- The piles were FRP jacketed.					
#06982	1936	Havre- 7th Ave N	2021	Bent 4: Pile 6. Bent 5: Pile 5. Bent 8: Pile 6. Bent 11: Pile 6. Bent 12: Pile 6. Bent 23: Pile 7. Bent 24: Pile 9. Bent 25: Piles 6, 8, 9, 12. Bent 27: Pile 5. Bent 28: Piles 5 and 9. Bent 29: Pile 8.	2022
- The piles were FRP jacketed.					