A FRAMEWORK FOR FIELD INSPECTION OF IN-SERVICE FRP REINFORCED/STRENGTHENED CONCRETE BRIDGE ELEMENTS:

Technical Summary

TECHNICAL REPORT DOCUMENTATION PAGE

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This document is a technical summary and supplement to the Florida International University report, A Framework for Field Inspection of In-Service FRP Reinforced/Strengthened Concrete Bridge Elements (FIU-800014727), available at https://rosap.ntl.bts.gov/view/dot/73333. The document additionally offers technical findings beyond those provided in the FIU report, based on the broader research study sponsored by the Federal Highway Administration (FHWA).</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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LIST OF ABBREVIATIONS AND SYMBOLS

Item	Description
AASHTO	American Association of State Highway and Transportation Officials
AE	acoustic emission testing
CFRP	carbon fiber reinforced polymer
DOT	Department of Transportation
FHWA	Federal Highway Administration
FIU	Florida International University
FRP	fiber reinforced polymer
FRP-RSC	fiber reinforced polymer-reinforced/strengthened concrete
GFRP	glass fiber reinforced polymer
GPR	ground penetrating radar
GSR	global structural response
IE	impact echo
IR	infrared thermography
IRT	impulse response testing
LT	laser testing
MFL	magnetic flux leakage
MW	microwave
NBIS	National Bridge Inspection Standards
NCHRP	National Cooperative Highway Research Program
NDE	non-destructive evaluation
NDT	non-destructive testing
NSM	near surface mounted
PAU	phased array ultrasonic testing
RC	reinforced concrete
RT	radiographic testing
SNBI	Specifications for the National Bridge Inventory
TT	tap testing
UT	ultrasonic testing
UV	ultraviolet
VT	visual inspection

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CHAPTER 1 — FRP APPLICATION

The application of Fiber Reinforced Polymer (FRP) materials in concrete bridge elements can be broadly classified as external and internal applications. The external application of FRP composites is primarily for the rehabilitation of structures when design deficiencies are noticed, the load-bearing capacity of an in-service element is modified, deterioration of materials has begun, or before or after extreme events have occurred (seismic or fire events). The internal application of FRP as concrete reinforcement is strongly justified for locations where corrosion of traditional steel reinforcement is an economic and safety concern. When compared to carbon steel rebars, FRP bars have higher strength, lower density, and can achieve a longer service life. Although the initial cost of FRP rebars is frequently highlighted as one of the main drawbacks to its implementation, it has changed significantly due the growth of the FRP rebar market.

In addition to the internal and external application of FRP for concrete elements, bridge elements that are made entirely or partly of FRP composites are being increasingly used. These applications are categorized under other applications of FRP which include stay-in-place (SIP) FRP forms, hybrid composite beams (HCB), concrete-filled FRP elements, FRP decks, and FRP composite bridge elements such as girders, trusses, piles, and cables. Figure 1 shows the summary of the several applications of FRP composites in bridge construction.

1.1. DEFICIENCIES IN FRP APPLICATION

While FRP bars may achieve improved durability and performance, deficiencies may be introduced during construction or throughout the course of its service life. FRP composites may be affected by environmental conditions (e.g., water, alkaline solutions, saline solutions, elevated temperature) and may exhibit deterioration (e.g., creep rupture, fatigue) due to mechanical factors that could affect the performance of the FRP reinforced/strengthened concrete (FRP-RSC) elements [2]. Load fluctuations in structures are often associated with cyclic fatigue. They produce the same phenomena as quasi-permanent loads associated with static fatigue, also referred to as creep-rupture (i.e., a composite loaded under constant stress may constantly strain until it cannot withstand further deformation, causing it to rupture). However, there are no special requirements for cyclic fatigue as provisions are covered under static fatigue.

Figure 2 shows a summary of potential deficiencies for FRP strengthened concrete bridge elements [3]. FRP-strengthened reinforced concrete (RC) elements typically consist of three parts: FRP, adhesive, and reinforced concrete, along with three interfaces: FRP-adhesive interface, adhesive-concrete interface, and concrete-steel reinforcement interface.

Figure 3 shows a summary of potential deficiencies in FRP reinforced concrete bridge elements [3].The concrete elements with internal FRP reinforcement are comprised of FRP, concrete, and concrete-FRP interfaces.

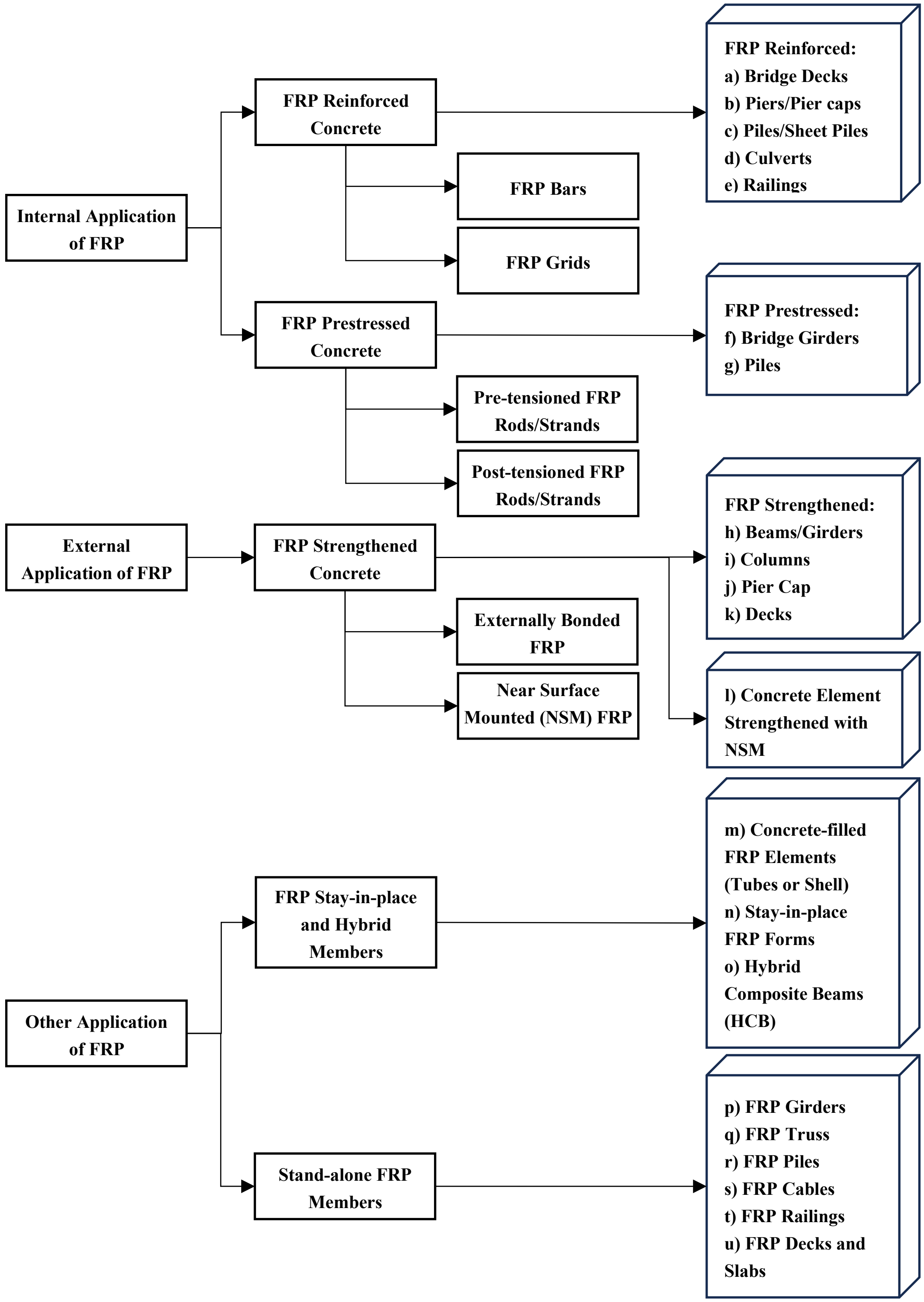


Figure 1. Illustration. Applications of FRP composites in bridge construction

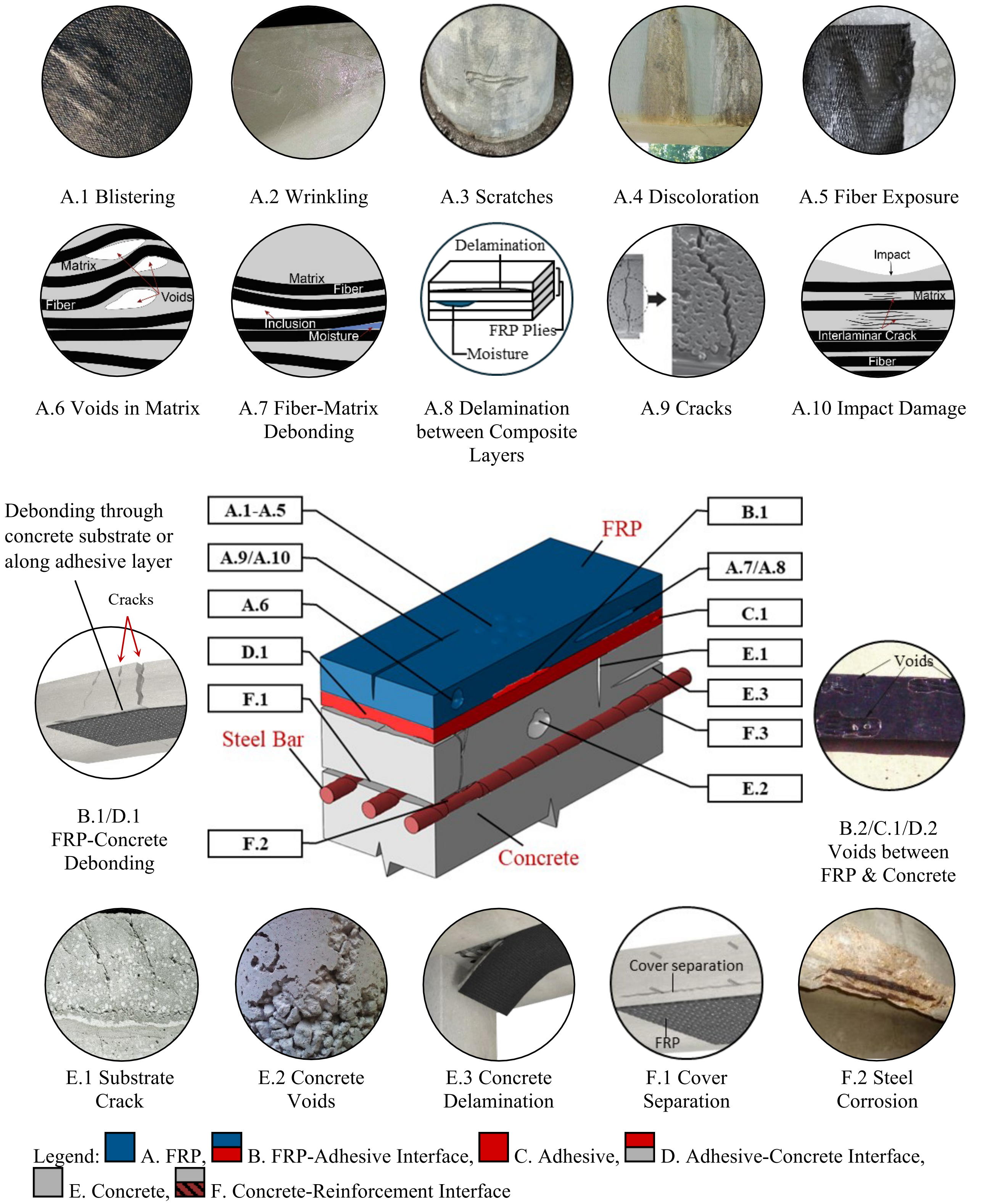


Figure 2. Illustration. Deficiencies in external FRP application

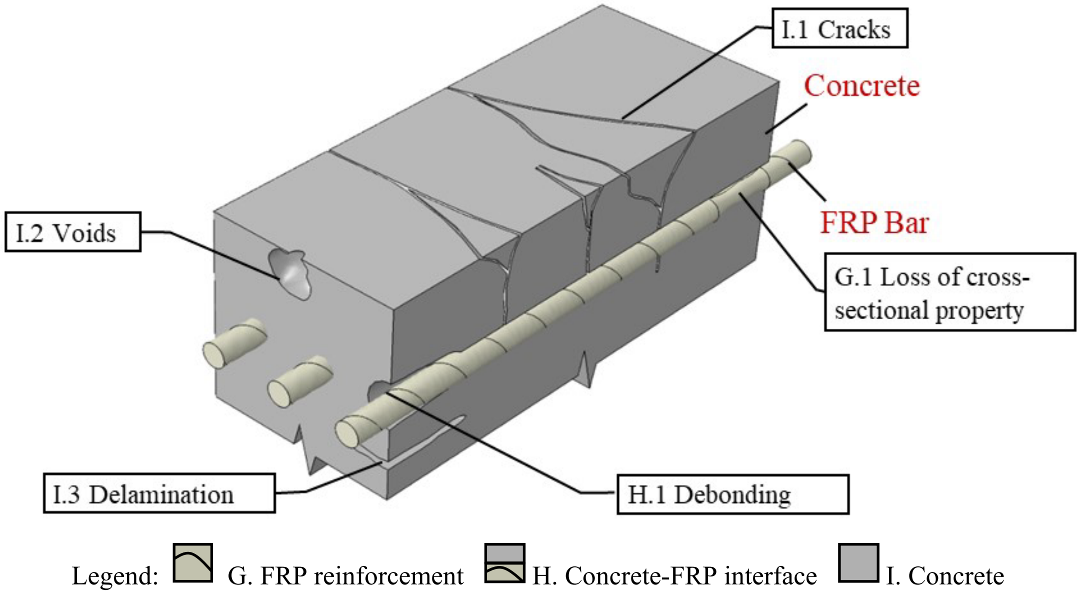


Figure 3. Illustration. Potential deficiencies in internal FRP application

1.2. NDT METHOD, INSPECTION METHODS, AND INSPECTION PROCEDURE

While extensive research has been performed for the application of Nondestructive Testing (NDT) and inspection methods in relation to conventional steel-reinforced concrete elements, there is limited research work conducted for FRP-RSC elements. There is also no clear guidance as to which methods are appropriate for detecting the deficiencies in FRP-RSC elements. To address this gap, this project investigated current NDT methods that can be applied to the inspection of FRP-RSC elements from a literature survey of past studies, applications, and research projects [4–6].

Ground Penetrating Radar (GPR) and Ultrasonic Testing (including Phased Array Ultrasonic, PAU) are recognized as NDT methods for detecting the presence of deficiencies in FRP-reinforced concrete that cannot easily be detected by visual inspection (VT) or tap testing (TT). In addition, infrared thermography (IR) was also identified as an applicable NDT method for FRP-strengthened concrete elements.

This project conducted several experimental tests to further investigate the applicability of the selected NDT methods in detecting the presence of deficiencies not easily identified by visual inspection or tap testing [7,8]. For the internal application, it was concluded that FRP bars/strands and their potential deficiencies can be detected using either GPR or PAU [9]. IR was effective in detecting deficiencies in externally applied FRP.

Furthermore, the project introduced two additional methods to enhance the detectability and deficiency detection in FRP bars and strands in concrete elements: applying a coating containing metallic particles and wire winding around the FRP bar surface [10].

1.2.1. Inspection Framework

The results of experimental work and the comprehensive literature review on the applicable inspection methods were used to develop a framework for inspection of in-service FRP-RSC bridge elements [1]. This inspection framework provides a comprehensive background on FRP composites, compares FRP application with respect to the conventional RC elements, recognizes and classifies various defects observed in FRP-RSC elements (Figure 4), and identifies nondestructive methods for the inspection of FRP-RSC elements. The flowchart presented in the framework for the selection of methods applicable for the inspection of concrete elements reinforced or strengthened with FRP is shown in Figure 5. The flowchart suggests various methods based on type of defects and type of FRP applications.

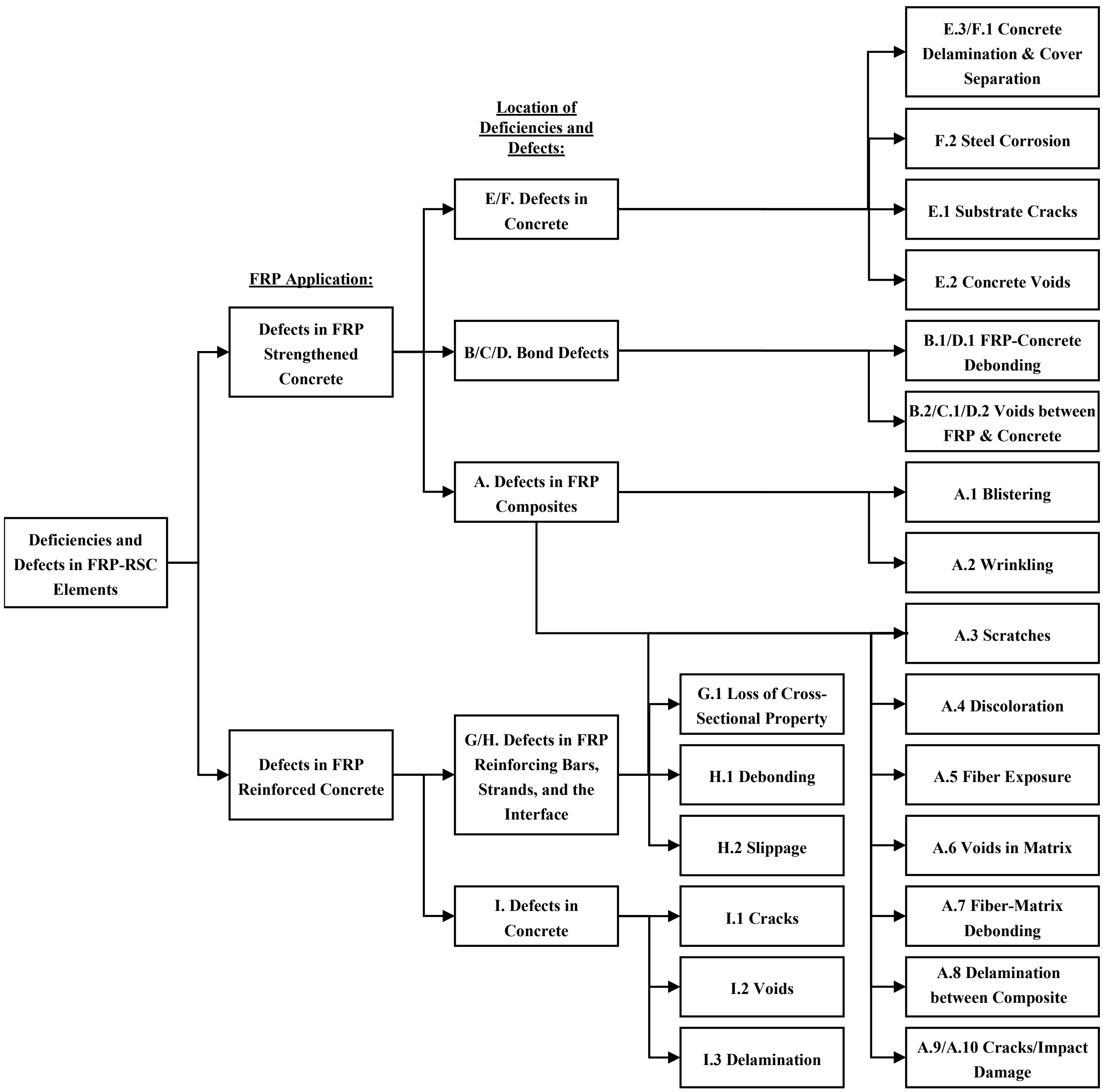
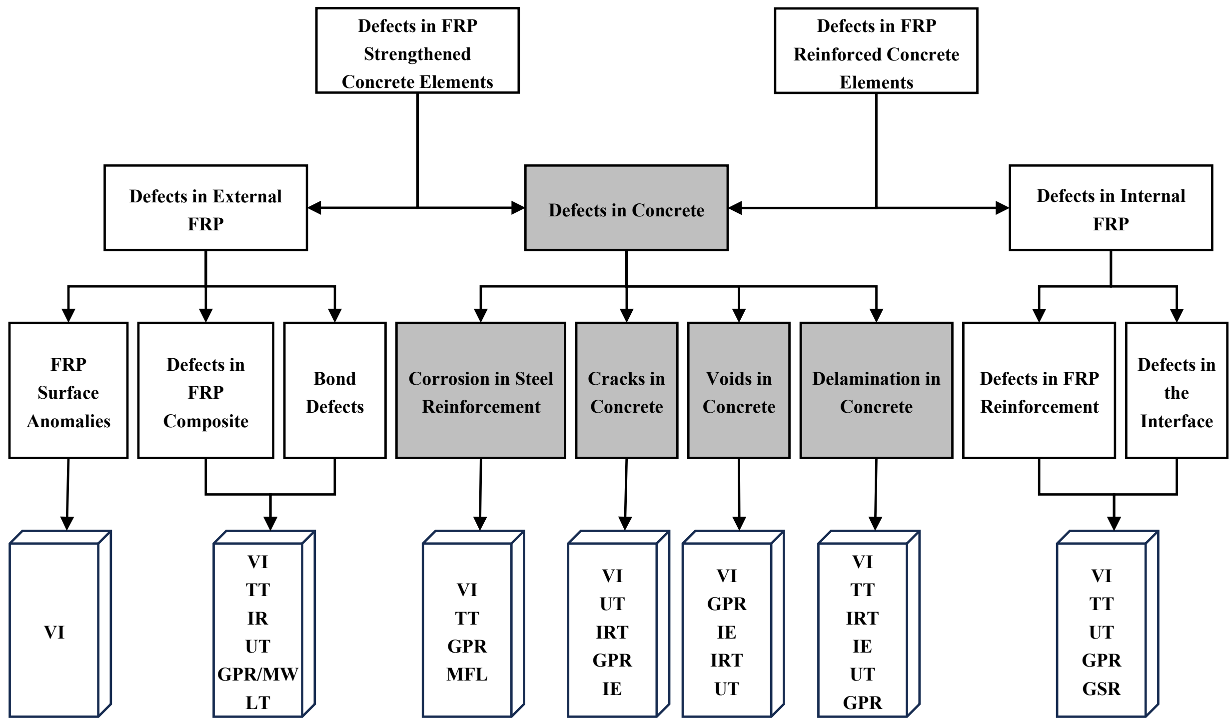


Figure 4. Illustration. Deficiencies in FRP-RSC members



Abbreviations:

VI = Visual Inspection, TT = Tap Testing, IE = Impact Echo, MW = Microwave, GPR = Ground Penetrating Radar, UT = Ultrasonic Testing, LT = Laser Testing, IR = Infrared Thermography, IRT = Impulse Response Testing, MFL = Magnetic Flux Leakage, GSR = Global Structural Response

Figure 5. Illustration. Suggested methods suitable for each type of defect.

The framework provides procedures, checklists of potential observations, and detailed forms to support inspection of FRP-RSC bridge elements and recording of their observations. It also indicates the instances that more sophisticated methods beyond visual inspection and tap testing may be warranted to be employed in the inspection process. For FRP-strengthened bridge elements, the inspection procedures have been presented for the inspection of surface anomalies, defects in FRP composite/bond issues, and defects in the concrete substrate (Table 1). Similarly, for FRP reinforced concrete bridge elements, inspection procedures for the inspection of concrete and internal FRP have been included (Table 2).

Table 1. Inspection procedures for FRP strengthened bridge elements (external application)

Inspection for	Visual Inspection, Tap Testing	NDT If Required
Surface Anomalies and Defects	• signs of surface anomalies such as blisters or bubble-like formations, fiber exposure, scratches, and cracks • regions of discoloration	• N/A
Defects in FRP Composite and Bond Issues	• signs of debonding and delamination in externally applied FRP • potential signs of voids • signs of moisture, water seepage, efflorescence, and water stains • use tap testing to identify location of debonding/delamination in addition to visual inspection	• areas suspected of having void can be further investigated using tap testing or IR • if warranted, detailed investigation of debonding, delamination and voids can be conducted using NDT methods suggested in Figure 5
Defects in Concrete Substrate	• signs of FRP tearing due to spalling of the concrete substrate • signs of rust stains, discoloration, or other visible abnormalities • signs of moisture, water seepage, efflorescence, and water stains	• NDT devices that can penetrate through the external FRP composite layer can be used at suspected areas

Table 2. Inspection procedure for FRP reinforced concrete elements (internal application)

Inspection for	Visual Inspection, Tap Testing	NDT If Required
Internal FRP	• signs of water seepage into the element • cracks in the FRP reinforced concrete elements • signs of distress such as fire damage with excessive spalling or burn marks • excessive deflection	• the presence of damage, its location, type, and severity in internal application of FRP can be further verified by using NDT methods suggested in Figure 5
Concrete	• follow the National Bridge Inspection Standards (23 CFR 650 Subpart C), as well as general purpose bridge inspection manuals and guides such as AASHTO - The Manual for Bridge Evaluation, AASHTO - Manual for Bridge Element Inspection, FHWA - Bridge Inspector's Reference Manual and others • refer to Figure 5 for more details on the selection of inspection methods for concrete inspection	

CHAPTER 2 — FRP AND THE SNBI

2.1. EXISTING FRP ITEM CODES

A framework for inventorying bridge components with FRP materials has not been available on a national scale until recently with the introduction of the Specifications for the National Bridge Inventory (SNBI[1]) [11]. The SNBI has expanded items and item codes available for the reporting of FRP materials in standalone and internal bridge components. Standalone FRP systems can be identified in the following items with the relevant FRP codes:

- Span Material (B.SP.04)
    - F01 FRP composite – aramid fiber
    - F02 FRP composite – carbon fiber
    - F03 FRP composite – glass fiber
    - FX FRP composite – other
- Deck Material and Type (B.SP.09)
    - F01 FRP composite – aramid fiber
    - F02 FRP composite – carbon fiber
    - F03 FRP composite – glass fiber
    - FX FRP composite – other
- Deck Stay in Place Forms (B.SP.13)
    - F01 FRP composite
- Substructure Material (B.SB.03)
    - F01 FRP composite – aramid fiber
    - F02 FRP composite – carbon fiber
    - F03 FRP composite – glass fiber
    - FX FRP composite – other
- Foundation Type (B.SB.06)
    - P09 Pile – FRP composite

Internal FRP application can be reported in the following item:

- Deck Reinforcing Protective System (B.SP.12)
    - R04 Reinforcing – FRP, aramid fiber
    - R05 Reinforcing – FRP, carbon fiber
    - R06 Reinforcing – FRP, glass fiber
    - R07 Reinforcing – FRP, other

The transition to the new SNBI items and item codes is comprehensive. One of the many benefits of the SNBI transition is that an inventory of FRP components and FRP codes is available on bridges in the National Bridge Inventory. Inventorying FRP is the first step in identifying the types and locations of FRP components.

[1] Specifications for the National Bridge Inventory (SNBI) is incorporated by reference in 23 CFR 650.317(b)(1).

2.2. FRP COMPONENT CONDITION DEFECTS

Determining the condition of the FRP systems is an important step in inspecting and managing FRP components. The condition of bridge components is recorded in the NBI separately: component condition ratings and element conditions. Component Condition Ratings are described below, and Element Conditions will be described in the next section.

The framework for assigning Component Condition ratings of standard materials such as steel and concrete for bridge components already exists in the SNBI[1]. The component condition rating codes consider the type, location, and severity of the defects; the extent to which they exist throughout the item being evaluated; and the degree to which the defects affect strength and/or performance of the bridge or component. The SNBI[1] uses a uniform condition rating scale of 0 to 9 that can be applied to all material-types to rate the general condition of bridges and culverts as shown in Table 3.

In addition to the uniform rating scale the SNBI also provides clarifying defect severity tables for common materials such as concrete, steel, timber, and masonry in Appendix C. The uniform condition rating scale in the SNBI and the defect severity tables in Appendix C of the SNBI can be combined to assign a uniform condition rating for the overall bridge component. Example component items in the SNBI that may have FRP systems include the following:

- B.C.01 Deck Condition Rating
- B.C.02 Superstructure Condition Rating
- B.C.03 Substructure Condition Rating
- B.C.04 Culvert Condition Rating
- B.C.05 Bridge Railing Condition Rating
- B.C.06 Bridge Railing Transitions Condition Rating

A framework for assigning FRP material-specific defects has not been available on a national scale until recently with the introduction of this research project. Tables 4 and 5 below can fit within the existing framework as a supplement to Appendix C in the SNBI and provide additional and clarifying defect severity tables for FRP applications.

Bridge owners can correlate the defect severity language in Table 4 and Table 5 within the component condition rating framework in Table 3, and assign a component condition rating for FRP components and systems.

Illustrative examples of combining both are provided in Figure 6 through Figure 9.

Table 3. SNBI Bridge condition rating [11]

Code	Condition	Description
9	Excellent	Isolated inherent defects.
8	Very good	Some inherent defects.
7	Good	Some minor defects.
6	Satisfactory	Widespread minor or isolated moderate defects.
5	Fair	Some moderate defects; strength and performance of the component are not affected.
4	Poor	Widespread moderate or isolated major defects; strength and/or performance of the component is affected.
3	Serious	Major defects; strength and/or performance of the component is seriously affected. Condition typically necessitates more frequent monitoring, load restrictions, and/or corrective actions.
2	Critical	Major defects; component is severely compromised. Condition typically necessitates frequent monitoring, significant load restrictions, and/or corrective actions in order to keep the bridge open.
1	Imminent Failure	Bridge is closed to traffic due to component condition. Repair or rehabilitation may return the bridge to service.
0	Failed	Bridge is closed due to component condition and is beyond corrective action. Replacement is required to restore service.

Table 4. Suggested defect severity for component condition ratings for FRP external application and FRP deck and slabs.

Defect	Minor	Moderate
Cracking, scratching, abrasion	Moderate-width or shallow cracks or scratches or abrasion mostly parallel to major stress or fiber directions	Wide or deep cracks or scratches or abrasion, especially if perpendicular to major stress or fiber directions but no through rupture or puncture.
Discoloration, fire damage	Shallow discoloration due to UV exposure or fire damage and protective coating degradation of 6” or less in diameter	Discoloration or UV exposure and protective coating degradation greater than 6” diameter. Brittleness distress or cracking is visible.
Blistering, voids, wrinkling	Blistering or voids 1” or less raised, or 6” or less in diameter.	Blistering or voids more than 1” raised, or greater than 6” in diameter.
Fiber exposure	Exposed at the surface, but not ruptured or debonded	Visibly exposed and debonded, but not ruptured
Delamination or debonding	Delamination 6” or less in diameter, away from connections or other sensitive details.	Delamination greater than 6” in diameter or near connections or sensitive details

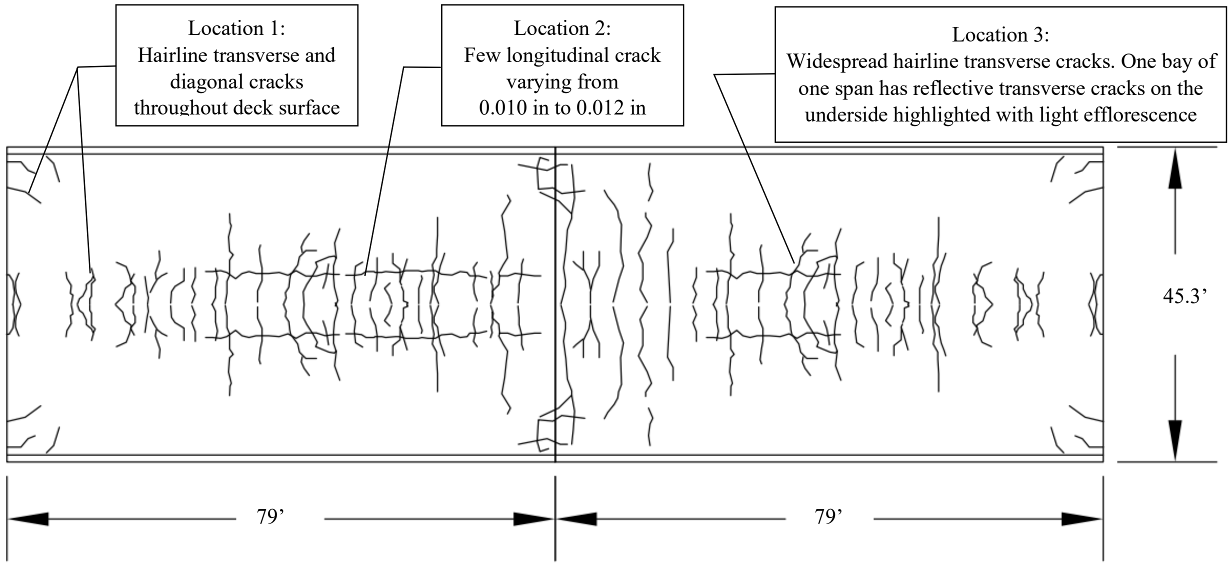
Table 5. Suggested defect severity for component condition ratings specific to FRP deck and slabs.

Defect	Minor	Moderate
Panel-to-Panel Joint / Panel-to-Girder Joint / Approach Joint	Evidence of joint degradation visible due to cracking in overlay or topping above panel joint locations. Gaps and cracks of up to 1/16 in.; no loss of bolts, clips, or other devices. Signs of water leakage through joints present.	Gaps, misalignment, and cracks of up to ¼ in. Few clips or bolts loose or lost, elevation changes for adjacent panels evident, crack movement observed with passing traffic loads. Free flow of water leakage through joints present.
Facesheet Debonding	None	Evidence such as noncritical damage to surrounding structural elements, reflective cracking at wearing surface or local damage to joints resulting in detection of debonding.

2.3. ILLUSTRATIVE COMPONENT CONDITION RATING FRP EXAMPLES

Example 1 - B.C.01 Deck Condition Rating: FRP Internal Application

An FRP-reinforced concrete bridge deck approximately 158’ long x 45.3’ wide with the following noted defects.



Deck plan view showing defects

Longitudinal cracks on deck surface. Location 2.

Some transverse hairline cracks with light efflorescence on the underside of the deck. Location 3.

Summary of Findings:

Location	Defect(s)	Severity	Extent
1	Transverse and diagonal cracks	Inherent	Throughout (widespread)
2	Longitudinal cracks	Minor	A few locations (isolated)
3	Transverse cracks with efflorescence on the bottom surface of the deck	Minor	One bay, one span (some)

Results: There are locations of widespread inherent cracks, isolated minor cracks, and some minor cracks. Therefore, the superstructure is best characterized as “some minor defects.”

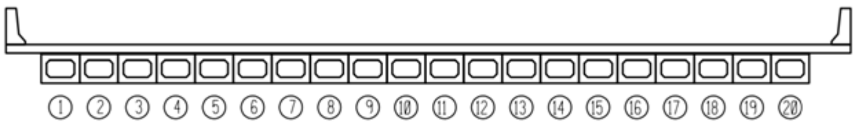
Report B.C.01 Deck Condition Rating: 7 – “Good”

Figure 6. Illustration. Deck Condition Rating Example.

Example 2 - B.C.02 Superstructure Condition Rating: FRP External Strengthened Application

A single-span adjacent box beam bridge. Each box beam is 3 ft. wide, 27 inches deep, and 54 ft. long.

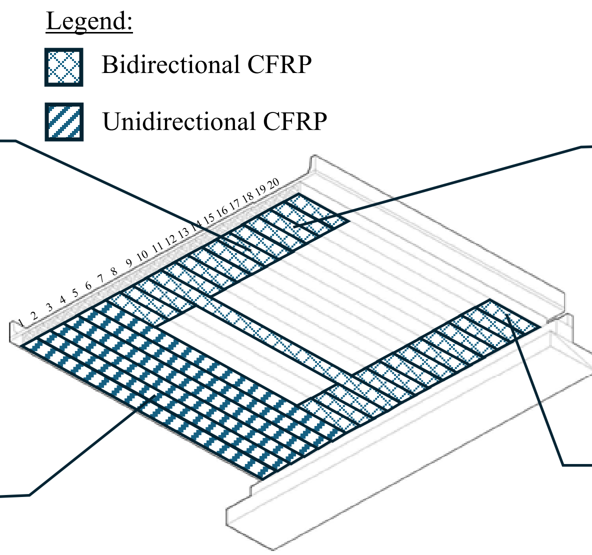
Rehabilitation history: Prior to retrofitting using CFRP, concrete deficiencies were previously identified throughout the superstructure, resulting in a condition rating of 3-Serious. To address these deficiencies, a waterproof overlay was added to prevent water infiltration through the deck and shear keys. The underside of the beams was strengthened with CFRP with fibers oriented parallel to the longitudinal axis of the beam. The concrete was repaired and cleaned prior to the installation of the FRP according to the manufacturer's recommendations. A load rating was performed to validate the external FRP strengthening improved the condition rating to 6. Around 25 years after retrofitting was completed, there are no additional defects found in the concrete. However, the following deficiencies in the external FRP were identified:

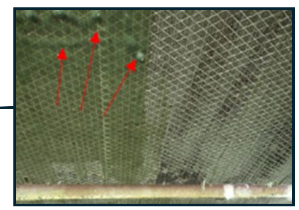


Cross-section view, looking south, with box beam numbering

Debonding and fiber exposure at Beam 15, 12 inches wide
Source: S. Milev, J. Tatar

Debonding, 12 inches wide, at Beam 2
Source: S. Milev, J. Tatar





Blistering, 1-inch diameter, at Beam 18
Source: S. Milev, J. Tatar

Fiber exposure, without debonding or rupture, at Beam 20
Source: S. Milev, J. Tatar

3D view of the box beams showing superstructure defect locations.

Summary of Findings:

Location	Defect(s)	Severity	Extent
Beam 18	Blistering	Minor	One location (isolated)
Beam 20	Fiber exposure	Minor	One location (isolated)
Beam 2	Debonding	Moderate	More than a few locations (some)
Beam 15	Debonding, fiber exposure	Moderate	One location (isolated)

Results: There are several instances of isolated minor, isolated moderate and some moderate defects that can be characterized together as "some moderate defects". These defects are on the FRP wrap and do not affect the strength or performance of the superstructure. Therefore, the superstructure is best characterized as "some moderate defects."

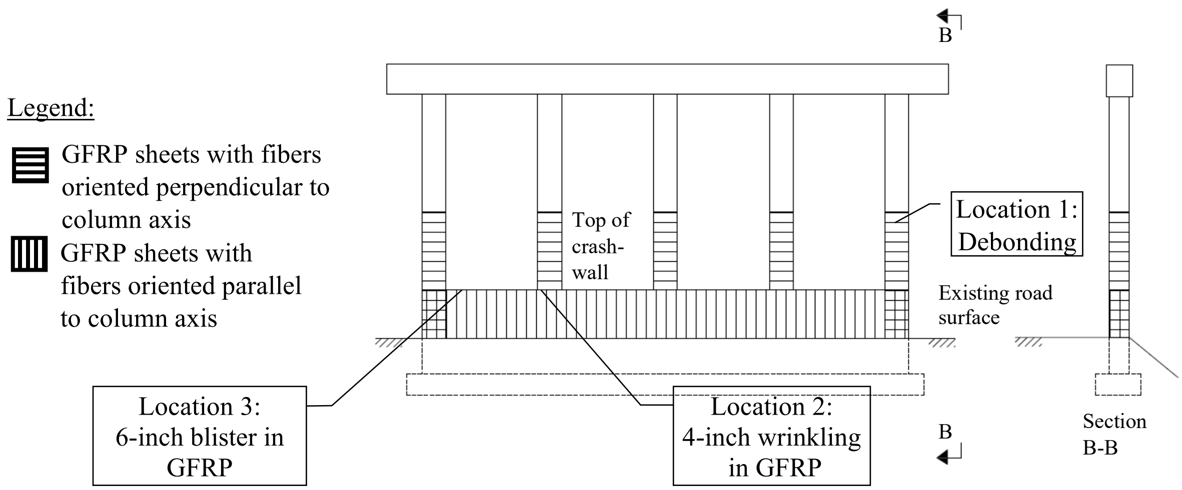
Report B.C.02 Superstructure Condition Rating: 5 – "Fair"

Figure 7. Illustration. Externally Strengthened Superstructure Condition Rating Example

Example 3 - B.C.03 Substructure Condition Rating: FRP External Application

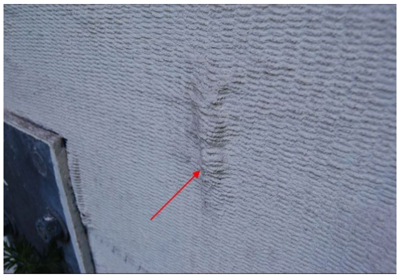
A continuous steel girder bridge with reinforced concrete piers comprised of a crashwall and rectangular (30″ × 36″) columns.

Rehabilitation History: Prior to retrofitting using GFRP, concrete spalling with exposed rebar that impacted strength and performance were previously identified only at Pier 2, resulting in a substructure condition rating of 4 - Poor. To address these deficiencies, the spalls were cleaned, the rebar was repaired and protected, and the concrete surface was prepared prior to the installation of the GFRP according to the manufacturer's recommendations. The crashwall was strengthened with GFRP sheets with fibers oriented parallel to the longitudinal axis of the column. The columns were strengthened with fibers oriented perpendicular to the longitudinal axis of the column. The columns were wrapped approximately 10 ft up measured from the top of the crashwall. The defects no longer impacted strength and performance. The rehabilitation resulted in the condition rating increasing to 6 - Fair. A few years after the rehabilitation was completed, there are no additional deficiencies found in the concrete. However, the following deficiencies in the external FRP were identified:

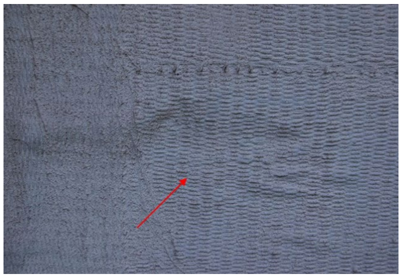


Elevation view of concrete column piers showing substructure defect locations

Debonding, 6-inch diameter, at the easternmost column of Pier 2. Location 1.
Source: Chris Williams



Wrinkling, 4 inches long, in GFRP sheet at crashwall of Pier 2. Location 2.
Source: Chris Williams



Blister, 6-inch diameter, below FRP sheet at crashwall of Pier 2. Location 3.
Source: Chris Williams

Summary of Findings:

Location	Defect(s)	Severity	Extent
1	Debonding	Minor	More than a few locations (some)
2	Wrinkling	Minor	One location (isolated)
3	Blistering	Minor	More than a few locations (some)

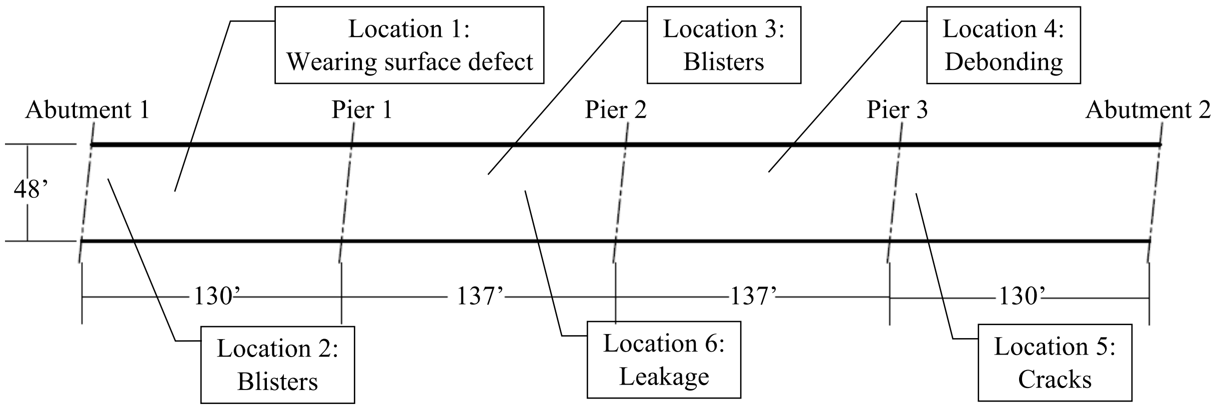
Results: There are instances of some minor defects that can be characterized together as "some minor defects." While the FRP is in good condition, the overall rating of the substructure is still fair.

Report B.C.02 Substructure Condition Rating: 6 – "Fair"

Figure 8. Illustration. Externally Strengthened Substructure Condition Rating Example

Example 4 - B.C.01 Deck Condition Rating: FRP Standalone Application

A four-span bridge with FRP deck supported over six built-up steel stringers. The FRP deck is protected by a thin overlay. The following defects are noted.



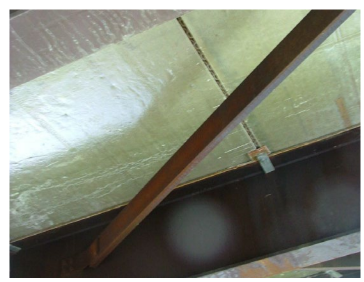
Deck plan view showing defects

Wearing surface delamination and minor scratch. Location 1.
Source: Chris Dumlao

Isolated blisters, 1-inch diameter. Locations 2 and 3.
Source: Chris Dumlao

Isolated debonding, 6-inch diameter. Location 4.
Source: Chris Dumlao

Isolated cracks and spalling in wearing surface above panel joints. Minor fiber exposure in FRP top surface. Location 5.
Source: Chris Dumlao



Minor water leakage through three panel joints. Location 6.
Source: Chris Dumlao

Summary of Findings:

Location	Defect(s)	Severity	Extent
1	Scratch	Minor	One location (isolated)
2 & 3	Blisters	Minor	One location (isolated)
4	Debonding	Minor	One location (isolated)
5	Cracks above panel-joints and spalling	Minor	More than a few locations (isolated)
6	Panel-to-panel joint leakage	Minor	3 panel joints (isolated)

Results: The defects are mostly in the protective wearing surface however they are evidence of deeper defects that impact the FRP deck. The nature of the several isolated defects can be combined and characterized together as “some minor.” Therefore, the deck is best characterized as “some minor defects.”

Report B.C.01 Deck Condition Rating: 7 – “Good”

Figure 9. Illustration. FRP Deck Rating Example

CHAPTER 3 — BRIDGE ELEMENT LEVEL INSPECTION BASED ON MBEI FOR EXTERNAL FRP APPLICATION ONLY FOR BRIDGE OWNERS TO CONSIDER

With the increasing use of FRP composites in bridge structures, this research findings suggest that FRP can be included as a new material for condition assessment in the Manual for Bridge Element Inspection (MBEI[2]) [12]. This report suggests that the bridge elements with internal application of FRP are mostly included under sections "3.1.1 – Reinforced Concrete" and "3.1.2 – Prestressed Concrete" in the MBEI[2] [12]. Only the bridge elements that can be constructed using FRP as the primary material as well as those bridge elements that use FRP externally for strengthening, repair and rehabilitation were identified for addition to the relevant sections of the Manual for Bridge Element Inspection (MBEI[2]) [12].

To represent the current applications of the FRP in bridges and provide a platform for future development, the following suggestions can be considered in addition to the Manual for Bridge Element Inspection (MBEI[2]) [12]:

- Add FRP material (underlined) to Tables 2.1.1, 2.1.2, 2.1.3, and 2.1.5 in Section 2 of the MBEI.
- Add new table "2.2.4 - FRP External Strengthening/Repair/Retrofit or Shell" under the article "2.2 Bridge Management Elements" to represent FRP strengthened bridge elements (underlined).
- Add new table "3.1.5A - FRP" to add FRP bridge members. The new table will provide a comprehensive listing of all elements made from FRP or strengthened with FRP (underlined).
- FRP can be included as one of the materials in the element commentary for different bridge components and sub-components in Article 3.2. Specifically, FRP (underlined) is added as one of the materials under the following bridge components and sub-components: Articles 3.2.3 "Railings", 3.2.3.2, 3.2.4.2 "Girders", and 3.2.4.4 "Trusses and Arches".
- A new Article 3.7A "FRP Elements" could be added to include defect listing and guidance on how to determine the condition state (CS) for each defect related to FRP elements or FRP strengthened elements (underlined).

These suggested additions that bridge owners can consider in addition to those in the MBEI[2] are presented in the following sections and underlined to show the additions.

[2] Manual for Bridge Element Inspection (MBEI) is incorporated by reference in 23 CFR 650.317(a)(4).

3.1. SUGGESTED ADDITIONS TO TABLE 2.1.1

Table 6. Items 32 and 33 can be included in Table 2.1.1 – Decks and Slabs.

Element	Units	Decks	Slab	Other
Reinforced Concrete Deck/Slab	area, ft^2	12	38	
Prestressed Concrete Deck	area, ft^2	13		
Prestressed Concrete Top Flange	area, ft^2	15		
Reinforced Concrete Top Flange	area, ft^2	16		
Steel Deck—Open Grid	area, ft^2	28		
Steel Deck—Concrete Filled Grid	area, ft^2	29		
Steel Deck—Corrugated/Orthotropic/Etc.	area, ft^2	30		
Timber Deck/Slab	area, ft^2	31	54	
FRP Deck/Slab	area, ft^2	32	33	
Other Material Deck/Slab	area, ft^2	60	65	

3.2. SUGGESTED ADDITIONS TO TABLE 2.1.2

Table 7. Item 335 can be included in Table 2.1.2 – Railings

Element	Units	Steel	Prestressed Concrete	Reinforced Concrete	Timber	Masonry	FRP	Other
Metal Bridge Railing	length, ft	330						
Reinforced Concrete Bridge Railing	length, ft			331				
Timber Bridge Railing	length, ft				352			
FRP Bridge Railing	length, ft						335	
Other Bridge Railing	length, ft							333
Masonry Bridge Railing	length, ft					334		

3.3. SUGGESTED ADDITIONS TO TABLE 2.1.3

Table 8. Items 171, 172, 173, 174, 175, 176, 177 and 178 can be included in Table 2.1.3 – Superstructure.

Element	Units	Steel	Prestressed Concrete	Reinforced Concrete	Timber	Masonry	FRP	Other
Girder/Beam	length, ft	107	109	110	111		171	112
Closed Web/Box Girder	length, ft	102	104	105			172	106
Stringer	length, ft	113	115	116	117		173	118
Truss	length, ft	120			135		174	136
Arch	length, ft	141	143	144	146	145	175	142
Floor Beam	length, ft	152	154	155	156		176	157
Cable—Primary	length, ft	147					177	
Cable—Secondary	each	148					178	149
Gusset Plate	each	162						
Pin, Pin and Hanger Assembly, or Both	each	161						

3.4. SUGGESTED ADDITIONS TO TABLE 2.1.5

Table 9. Item 237 can be included in Table 2.1.5 – Substructure.

Element	Units	Steel	Prestressed Concrete	Reinforced Concrete	Timber	Masonry	FRP	Other
Columns	each	202	204	205	206			203
Column Tower (Trestle)	length, ft	207		237	208	238		
Pier Wall	length, ft			210	212	213		211
Abutment	length, ft	219		215	216	217		218
Pile	each	225	226	227	228		237	229
Pier Cap	length, ft	231	233	234	235			236
Pile Cap/Footing	length, ft			220				

3.5. SUGGESTED ADDITIONS OF NEW TABLE 2.2.4

Table 10. Items 601, 602, 603, and 604 can be included in a new table, Table 2.2.4 – FRP External Strengthening

Element/Component	Units	Element Number
FRP Sheets	area, ft^2	601
FRP Pultruded Laminate	area, ft^2	602
FRP Near-Surface Mounted Reinforcing Bars	length, ft	603
FRP Post-Tensioning	length, ft	604

3.6. SUGGESTED ADDITION OF NEW TABLE 3.1.5A

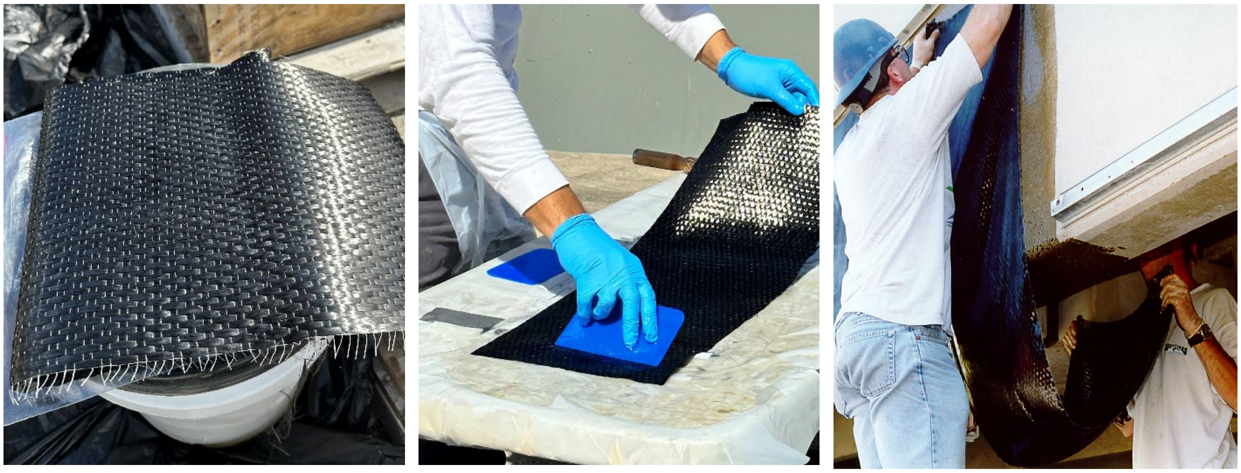
Table 11. Items 32, 33, 335, 171, 172, 173, 174, 175, 176, 177, 178, 237, 601, 602, 603, and 604 can be included in new Table 3.1.5A – FRP

DECKS AND SLABS						
32	**FRP Deck**		Classification	**NBE**	Unit of Measure	**ft^2**
	Description:	All FRP bridge decks regardless of the wearing surface or protection systems used.				
	Quantity Calculation:	Area of the deck from edge to edge, including any median areas and accounting for any flares or ramps present.				
33	**FRP Slab**		Classification	**NBE**	Unit of Measure	**ft^2**
	Description:	All FRP bridge slabs regardless of the wearing surface or protection systems used.				
	Quantity Calculation:	Area of the slab from edge to edge, including any median areas and accounting for any flares or ramps present.				
RAILINGS						
335	**FRP Bridge Railing**		Classification:	**NBE**	Unit of Measure	**ft**
	Description	All types and shapes of FRP bridge railing. All or some elements of the railing are FRP.				
	Quantity Calculation	Number of rows of bridge rail (or FRP components) times the length of the bridge. The element quantity includes only the rail on the bridge.				
	Note:	This element does not include concrete rails reinforced with FRP bars.				
SUPERSTRUCTURE						
172	**FRP Closed Web/Box Girder**		Classification:	**NBE**	Unit of Measure:	**ft**
	Description:	All FRP box girders or closed web girders. For all box girders regardless of protective system.				
	Quantity Calculation:	Sum of all the length of each box girder section. This quantity can be determined by counting the visible web faces, dividing by two, and then multiplying by the appropriate length of the box section. Elements such as adjacent box girders are considered individual girders.				
171	**FRP Open Girder/Beam**		Classification:	**NBE**	Unit of Measure:	**ft**
	Description:	FRP open web girders regardless of protective system.				
	Quantity Calculation:	Sum of all of the lengths of each girder.				
173	**FRP Stringer**		Classification:	**NBE**	Unit of Measure:	**ft**
	Description:	FRP members that support the deck in a stringer floor beam system regardless of protective system.				
	Quantity Calculation:	Sum of all of the lengths of each stringer.				
174	**FRP Truss**		Classification:	**NBE**	Unit of measure:	**ft**
	Description:	All FRP truss elements, including all tension and compression members for through and deck trusses. For all trusses regardless of protective system.				

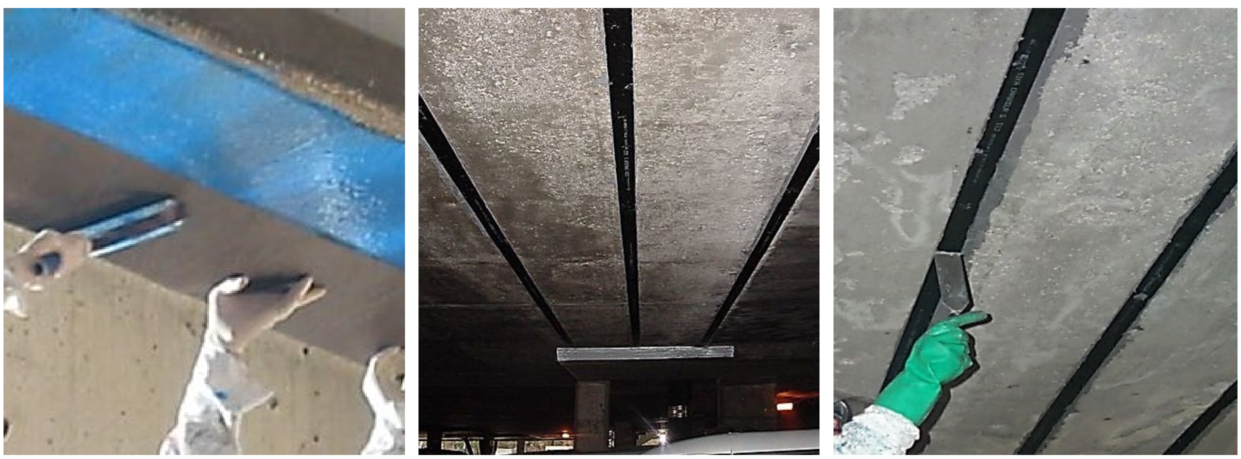
	Quantity Calculation:	Sum of all of the lengths of each truss panel measured longitudinally along the travel way.				
175	**FRP Arch**		Classification:	**NBE**	Unit of Measure:	**ft**
	Description:	Arch made of FRP as main load bearing element or FRP individual arches used in assembly of elements.				
	Quantity Calculation:	Sum of all of the lengths of each arch panel measured longitudinally along the travel way.				
176	**FRP Floor Beam**		Classification:	**NBE**	Unit of Measure:	**ft**
	Description:	FRP floor beams that typically support stringers regardless of protective system.				
	Quantity Calculation:	Sum of all of the lengths of each floor beam.				
177	**FRP Main Cables**		Classification:	**NBE**	Unit of measure:	**ft**
	Description:	All FRP suspension or cable stay cables for all cable groups regardless of protective systems.				
	Quantity Calculation:	Sum of all of the lengths of each main cable measured longitudinally along the travel way.				
	Note:	This element is intended for use on main cables in suspension bridges or main cable stays in cable stayed bridges. Suspender cables or other smaller cables shall be captured using Element 178 below.				
178	**FRP Secondary Cables**		Classification:	**NBE**	Unit of measure:	**ea**
	Description:	All FRP suspended cables for all individual or cable groups regardless of protective systems.				
	Quantity Calculation:	Sum of the individual cable or cable groups carrying the load from the superstructure to the main cable/arch elements.				
	Note:	This element is intended for use on suspender cables, other smaller cables, or groups of cables in one location acting as a system to carry loads from the superstructure to the main cable/arch. Suspension bridge main cables or cable stays shall be captured using Element 177 above.				
SUBSTRUCTURE						
237	**FRP Pile**		Classification:	**NBE**	Unit of Measure:	**ea**
	Description:	FRP piles that are visible for inspection, including piles exposed from erosion or scour and piles visible during an underwater inspection. For all FRP piles regardless of protective system				
	Quantity Calculation:	Sum of the number of piles visible for inspection.				
FRP External Strengthening/Repair/Retrofit or Shell						
601	**FRP Sheets**		Classification:	**BME**	Unit of Measure:	**ft^2**
	Description:	Layered FRP sheets or wraps, usually a woven cloth, normally saturated and installed at site, for strengthening/repair/rehabilitation regardless of the type of substrate material.				

	Quantity Calculation:	Area of FRP sheet application.				
	Notes:	This can also include factory-made layup to create a shell which serves as stay-in-place form.				
602	**FRP Pultruded Laminate**		Classification:	**BME**	Unit of Measure:	**ft^2**
	Description:	FRP pultruded laminates, such as plates or shells, prefabricated at shop and attached to an element for strengthening/repair/rehabilitation regardless of the type of substrate material.				
	Quantity Calculation:	Area of FRP laminate application.				
	Notes:	This can also include prefabricated shells to serve as stay-in-place forms.				
603	**FRP Near Surface Mounted (NSM) Reinforcing Bars**		Classification:	**BME**	Unit of Measure:	**ft**
	Description:	FRP reinforcing bars placed in grooves cut in the substrate material and covered by grout or resin for strengthening/repair/rehabilitation regardless of the type of substrate material.				
	Quantity Calculation:	Sum of all the lengths of reinforcing bars				
604	**FRP Post-Tensioning**		Classification:	**BME**	Unit of Measure:	**ft**
	Description:	FRP post-tensioning bars, strands, or laminates for elements bonded to or separate from the substrate, regardless of the type of substrate material.				
	Quantity Calculation:	Sum of all the lengths of post-tensioning bars, strands, or laminates				
	Notes:	Anchorage devices are not covered in this item.				

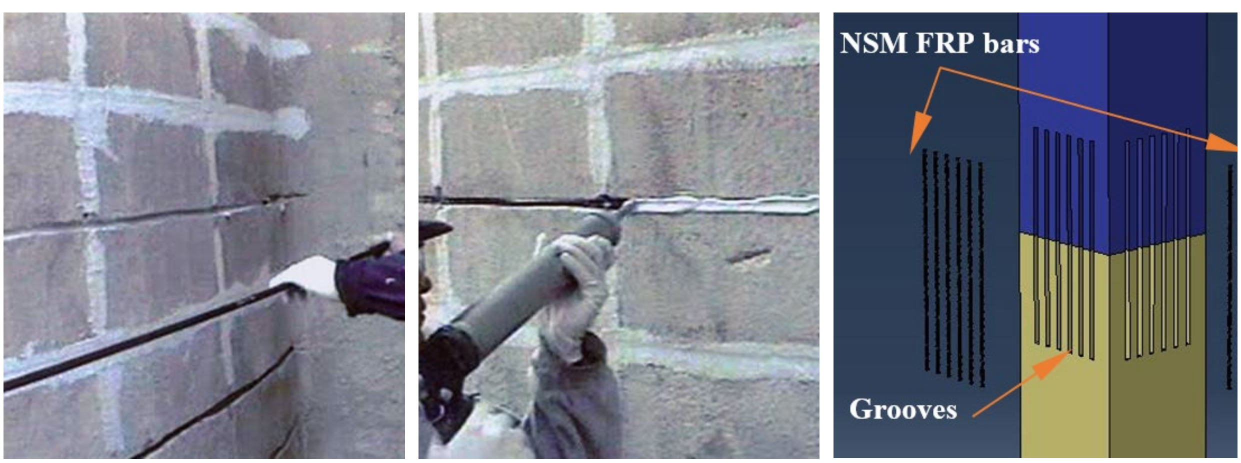
*: These elements are to be considered independently from the elements they are attached to.



601 FRP Sheets



602 FRP Pultruded Laminate



603 FRP Near Surface Mounted (NSM) Reinforcing Bars

Figure 10. Illustrative Example. FRP External Strengthening Elements 601-604

604 FRP Post-Tensioning
Source: [13]

Figure 10. Illustrative Example. FRP External Strengthening Elements 601-604 (Continued)

3.7. SUGGESTED ADDITIONS TO ARTICLE 3.2.3

FRP is suggested to be included in section **3.2.3 – Railings**

3.2.3 Railings

These elements cover bridge rail, which may be fabricated from steel, other metal, concrete, masonry, FRP, and other materials.

3.2.3.2

For assessing the condition of posts, blocking, and curbs that are formed from a different material than the railing, refer to the appropriate bridge railing material elements (i.e., metal, concrete, timber, masonry, FRP, or other) for specific defects.

3.8. SUGGESTED ADDITIONS TO ARTICLE 3.2.4

FRP is suggested to be included in section **3.2.4 – Superstructure**

3.2.4.2 Girders

These elements transmit the loads from the deck into the substructure. Elements listed include closed web (boxes) and open girders (I-sections). The materials include steel, reinforced and prestressed concrete, FRP, and timber.

3.2.4.4 Trusses and Arches

These superstructure elements include materials of steel, concrete, timber, FRP, and masonry; they are the main load-carrying members for the span.

3.9. SUGGESTED ADDITION OF NEW ARTICLE 3.7A

Items 32, 33, 335, 171, 172, 173, 174, 175, 176, 177, 178, 237, 335, 601, 602, 603, and 604 can be included in a new Section **3.7A, "FRP Elements".**

Element No.	**Element Name**	**Classification**	**Units of Measurement**	**Element No.**	**Element Name**	**Classification**	**Units of Measurement**
Decks and Slabs				**Substructure**			
32	FRP Deck	NBE	ft^2	237	FRP Pile	NBE	ea
33	FRP Slab	NBE	ft^2	**Railing**			
Superstructure				335	FRP Bridge Railing	NBE	ft
171	FRP Open Girder/Beam	NBE	ft	**FRP External Strengthening/Repair/Retrofit or Shell**			
172	FRP Closed Web/Box Girder	NBE	ft	601	FRP Sheets	BME	ft^2
173	FRP Stringer	NBE	ft	602	FRP Pultruded Laminate	BME	ft^2
174	FRP Truss	NBE	ft	603	FRP Near Surface Mounted (NSM) Reinforcing Bars	BME	ft
175	FRP Arch	NBE	ft	604	FRP Post-tensioning bars/strands/laminates	BME	ft
176	FRP Floor Beam	NBE	ft				
177	FRP Main Cables	NBE	ft				
178	FRP Secondary Cables	NBE	ea				

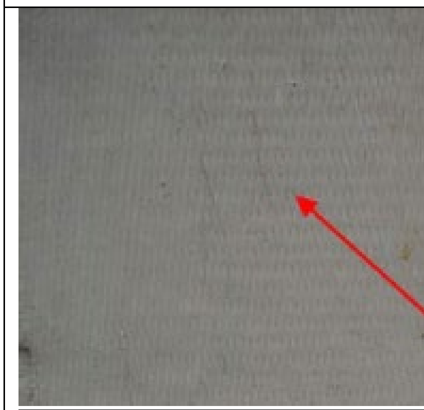
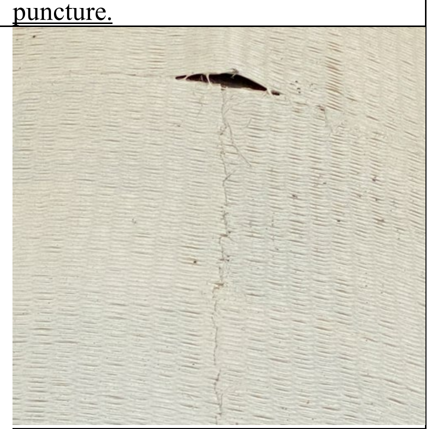
Defects for FRP

Defects	Condition States			
	CS 1	**CS 2**	**CS 3**	**CS 4**
	GOOD	**FAIR**	**POOR**	**SEVERE**
Defects for FRP-Strengthened Elements and FRP deck and slabs				
Cracking (1230) Scratches (1240) Abrasion (1290)	None	Shallow cracks, scratches, or abrasion, limited to the polymer, with no fibers visible and parallel to the major stress direction.	Wide or deep cracks or scratches or abrasion, especially if perpendicular to major stress or fiber directions but no through rupture or puncture.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element.
Wrinkling (1210) Voids (1270) Blister (1260)	None	Less than 1 inch raised or less than 6 inches in diameter or length.	More than 1 inch raised or more than 6 inches in diameter or length.	
Discoloration (1250) and Fire Damage (1215)	None, or cosmetic stain or fire mark	Permanent shallow discoloration or UV exposure and protective coating degradation 6 inches in diameter or less.	Permanent discoloration or UV exposure with cracking, brittleness, or distress, or more than 6 inches in diameter.	
Fiber Exposure (1280)	None	Exposed but not ruptured, buckled, or debonded at the surface damage location.	Fibers exposed and debonded (especially in cracks perpendicular to major stress or fiber directions) but not buckled or ruptured at the surface damage location.	
Delamination/debonding (interlaminar/from substrate) (1205)	None	Delamination smaller in every dimension than 6 inches but away from sensitive details (e.g., connections) to have structural effects.	Delamination smaller in every dimension than 6 inches but near sensitive details (e.g., connections) to have structural effects.	
Defects applicable only to FRP deck and slab (adapted from NCHRP report 564)				
Panel-to-Panel Joint (1225) Panel-to-Girder Joint (1235) Approach Joint (1245)	None	Evidence of joint degradation visible due to cracking in overlay or topping above panel joint locations. Gaps and cracks of up to 1/16 inch; no loss of bolts, clips, or other devices. Leakage may be minimal.	Gaps, misalignment, and cracks of up to ¼ inch in overlay. Few clips or bolts loose or lost, minor elevation changes for adjacent panels evident. Leakage may be moderate, more than a drip and less than a free flow of water.	

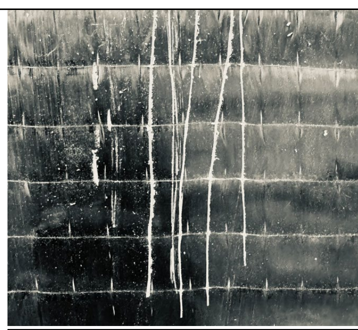
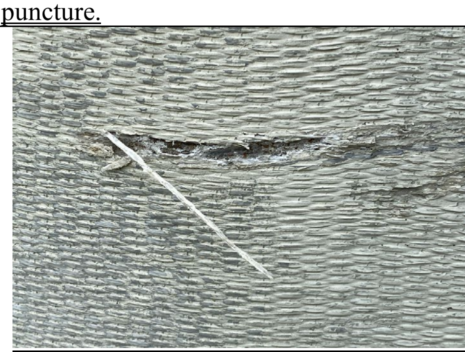
Defects	Condition States			
	CS 1	**CS 2**	**CS 3**	**CS 4**
	GOOD	**FAIR**	**POOR**	**SEVERE**
Facesheet Debonding (1255)	None	Visible minor bulge or peeling on the top surface indicating initiation of debonding.	Noncritical damage to surrounding structural elements, such as reflective cracking at wearing surface or local damage to joints resulting in detection of debonding.	
General				
Settlement (4000)	None	Exists within tolerable limits or arrested with no observed structural distress.	Exceeds tolerable limits but does not warrant structural review.	
Scour (6000)	None	Exists within tolerable limits or has been arrested with effective countermeasures.	Exceeds tolerable limits but is less than the critical limits determined by scour evaluation and does not warrant structural review.	
Damage (7000)	Not applicable	The element has impact damage. The specific damage caused by the impact has been captured in CS 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in CS 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in Condition State 4 under the appropriate material defect entry.

Note: This table is provided as a general suggestion for recognizing the condition state. The inspector may use engineering judgement to recognize exceptions. If any damage, regardless of its extent, is perceived to affect the structural integrity of the element, it should be noted as State 4 or severe.

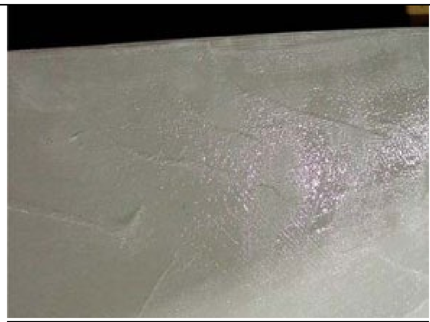
Defect 1230 Cracking (FRP)

Condition State 1	Condition State 2	Condition State 3
Hairline surface cracks	Shallow cracks limited to the polymer, with no fibers visible and parallel to the major stress direction.	Wide or deep cracks, especially if perpendicular to major stress or fiber directions but no through rupture or puncture.
		

Defect 1240 Scratches (FRP)

Condition State 1	Condition State 2	Condition State 3
None	Shallow scratches limited to the polymer, with no fibers visible and parallel to the major stress direction.	Wide or deep scratches, especially if perpendicular to major stress or fiber directions but no through rupture or puncture.
		

Defect 1290 Abrasion (FRP)

Condition State 1	Condition State 2	Condition State 3
None	Shallow abrasion, limited to the polymer, with no fibers visible and parallel to the major stress direction.	Wide or deep abrasion, especially if perpendicular to major stress or fiber directions but no through rupture or puncture.
		

Defect 1210 Wrinkling (FRP)

Condition State 1	Condition State 2	Condition State 3
None	Less than 1 in. raised or less than 6 inches diameter or length.	More than 1 in. raised or more than 6 inches in diameter or length.
		

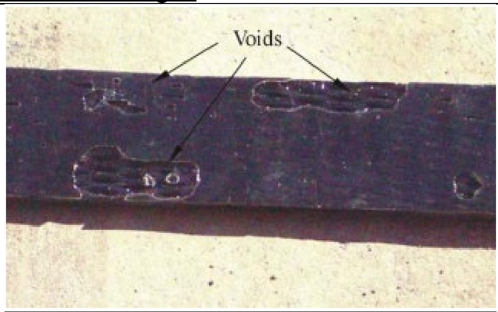
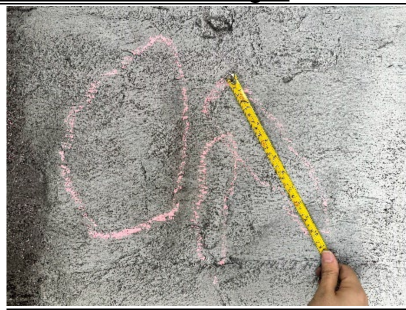
Defect 1250 Discoloration (FRP)

Condition State 1	Condition State 2	Condition State 3
None or none after cleaning superficial stain	Permanent shallow discoloration or UV exposure and protective coating degradation of 6 inches in diameter or less.	Permanent discoloration or UV exposure with cracking, brittleness, or distress, or more than 6 inches in diameter.
		 Source: [14]

Defect 1260 Blister (FRP)

Condition State 1	Condition State 2	Condition State 3
None	Less than 1 inch raised or less than 6 inches in diameter or length.	More than 1 inch raised or more than 6 inches in diameter or length.
		

Defect 1270 Voids (FRP)

Condition State 1	Condition State 2	Condition State 3
None	Less than 1 inch raised or less than 6 inches in diameter or length.	More than 1 inch raised or more than 6 inches in diameter or length.
	 Source: [15]	

Defect 1280 Fiber Exposure (FRP)

Condition State 1	Condition State 2	Condition State 3
None	Exposed but not ruptured, buckled, or debonded at the surface damage location.	Fibers exposed and debonded (especially in cracks perpendicular to major stress or fiber directions), but not buckled or ruptured at the surface damage location.
		 Source: [16]

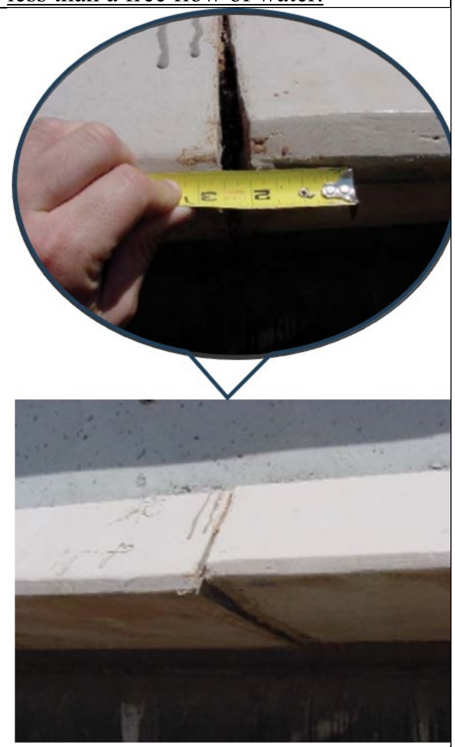
Defect 1205 Delamination/Debonding (FRP)

Condition State 1	Condition State 2	Condition State 3
None	Delamination smaller in every dimension than 6 inches but away from sensitive details (e.g., connections) to have structural effects.	Delamination smaller in every dimension than 6 inches but near sensitive details (e.g., connections) to have structural effects.
		 Source: [14]

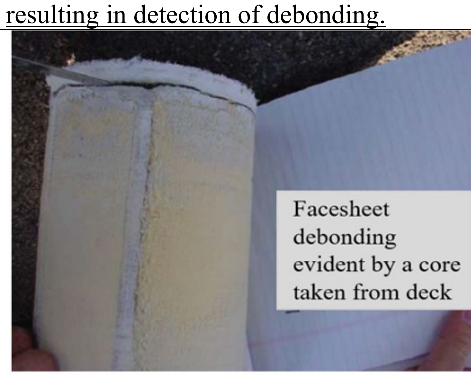
Defect 1215 Fire Damage (FRP)

Condition State 1	Condition State 2	Condition State 3
None or none after cleaning superficial stain or fire mark	Permanent shallow discoloration 6 inches in diameter or less.	Permanent discoloration and with cracking, brittleness, or distress or more than 6 inches in diameter.
		

Defect 1225, 1235, 1245 Panel Joints (FRP)

Condition State 1	Condition State 2	Condition State 3
Minor deterioration with hairline cracks less than 1/32 in. No noticeable water leakage observed from underside.	Evidence of joint degradation visible due to cracking in overlay or topping above panel joint locations. Gaps and cracks of up to 1/16 inch; no loss of bolts, clips, or other devices. Signs of water leakage maybe minimal.	Gaps, misalignment, and cracks of up to ¼ inch in overlay. Few clips or bolts loose or lost, minor elevation changes for adjacent panels evident. Leakage may be moderate, more than a drip and less than a free flow of water.
		

Defect 1255 Facesheet Debonding (FRP)

Condition State 1	Condition State 2	Condition State 3
None	Visible minor bulge or peeling on the top surface indicating initiation of debonding.	Noncritical damage to surrounding structural elements, such as reflective cracking at wearing surface or local damage to joints resulting in detection of debonding.
		

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