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

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16. Abstract

The main objective of this project is to develop the framework for inspection and condition assessment of in-service FRP reinforced/strengthened concrete (FRP-RSC) bridge elements. The framework applies to both FRP reinforced structures (FRP internal application) and FRP strengthened structures (FRP external application) and conforms with National Bridge Inspection Standard (NBIS). This framework will be also applicable to other structural components that have incorporated FRP materials including Hybrid Composite Beams (HCB), Concrete-Filled Arch, and Tub girders. This research project highlights the similarities and differentiating aspects between conventionally reinforced concrete and FRP-RSC elements. The report presents the information available to-date and innovative approaches to develop or adapt tools and methods of evaluation to fill the gaps in the knowhow. Since many aspects of FRP application are still evolving, the framework may be updated as more information becomes available.

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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)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		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)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		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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The FHWA is the source of all figures and photographs within this document unless noted otherwise.

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LIST OF ABBREVIATIONS AND SYMBOLS

ITEM	Descriptions
AAR	alkali-aggregate reaction
AASHTO	American Association of State Highway and Transportation Officials
ABC	Accelerated Bridge Construction
ACI	American Concrete Institute
ACR	alkali carbonate reaction
AE	acoustic emission testing
AFRP	aramid fiber reinforced polymer
ASR	alkali-silica reaction
ASTM	American Society for Testing and Materials
BFRP	basalt fiber reinforced polymer
CATT	computer-aided tap tester
CFRP	carbon fiber reinforced polymer
CSA	Canadian Standards Association
CSP	Concrete Surface Profile
DOT	Department of Transportation
DPT	dye penetrant testing
DTT	digital tap testing
EB	externally bonded
ECT	eddy current testing
EMBS	embedded FRP bars or strands
ETL	equivalent time length
EXBS	externally bonded FRP sheets
FHWA	Federal Highway Administration
FIU	Florida International University
FRP	fiber reinforced polymer
FRP RC	fiber reinforced polymer reinforced concrete
FRP-RSC	fiber reinforced polymer-reinforced/strengthened concrete
GFRP	glass fiber reinforced polymer
GPR	ground penetrating radar
GSR	global structural response
HW	helically wrapped
HWSC	helically wrapped sand coated
ICRI	International Concrete Repair Institute
IE	impact echo testing
IR	infrared thermography testing
IRT	impulse response testing
JPCI	Japan Prestressed Concrete Institute
JSCE	Japan Society of Civil Engineers
LRFD	Load and Resistance Factor Design
LT	laser testing
MFL	magnetic flux leakage testing
MOT	maintenance of traffic
MW	microwave testing
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
PC	prestressed concrete
RC	reinforced concrete
RT	radiographic testing
SC	sand coated
SML	Structures and Materials Laboratory
TT	tap testing
UAV	unmanned aerial vehicle
UD	unidirectional
UT	ultrasonic testing
UV	ultraviolet
VT	visual inspection

SECTION 1 INTRODUCTION

1.1 PURPOSE

While inspection methods and codification of deficiencies have been in use for a long time for conventional steel and reinforced concrete bridges, a standardized and unified methodology or framework for inspection and damage detection of concrete bridge elements reinforced or strengthened with fiber reinforced polymer (FRP) does not exist. The lack of clear guidelines and effective methods for condition assessment of FRP reinforced/strengthened concrete (FRP-RSC) elements could have negatively affected the proliferation of its use. Availability of such means and methods will have positive effects in increasing the use of FRP-RSC.

This inspection framework is based on the findings of research funded by the Federal Highway Administration (FHWA). This Framework for Field Inspection of In-service FRP Reinforced/ Strengthened Concrete Bridge Elements presented here contains the information available to date from other sources and work performed by the authors. It also represents the foundation of framework for inspection and condition assessment of in-service FRP-RSC bridge elements that can be built upon new information that will become available in the future. The framework also comes with an accompanying report containing details on each subject.

1.2 APPLICABILITY

The framework can be readily used by inspectors and practitioners and alleviates the concerns by bridge owners of uncertainties associated with condition assessment of bridges using FRP and their maintenance. Although FRP has been used with different materials such as steel, timber and masonry in bridge structures, this framework will specifically focus on the use of FRP with concrete bridge elements. The primary impact of this framework is to ensure safety and integrity of bridges using FRP. Development of this framework serves as an effective catalyst to take advantage of many benefits of FRP for construction of bridges.

1.3 INTENDED USERS

This framework targets bridge engineering professionals and inspectors who inspect, assess, or evaluate FRP-RSC bridge elements. This framework provides comprehensive background on FRP composites, compares design and installation/construction with respect to the conventional reinforced concrete (RC) elements, recognizes and classifies various deficiencies observed in FRP-RSC elements, and identifies non-destructive methods for the inspection of FRP-RSC elements.

1.4 ORGANIZATION

The framework is organized into six sections as follows:

Section 1 – Introduction: This section provides the purpose of this framework, its expected outcomes and impact, its organization, and guidance on how to use this framework.

Section 2 – Background: This section provides background on composition of FRP composites, the manufacturing process of FRPs used in bridges and the application of FRP in concrete bridge elements.

Section 3 – FRP Design and Installation Practices: This section provides details on the available standards and design specifications for repair and strengthening of reinforced concrete bridge elements, and design of structural concrete bridge members reinforced with FRP; along with the serviceability limits for FRP-RSC elements. Further, this section provides information on the construction specifications and installation practices for the FRP-RSC elements.

Section 4 – Deficiencies in FRP Application: This section discusses the identification and classification of observed deficiencies in FRP-RSC elements. In addition, it introduces the possible sources of those deficiencies whose presence could be an indication that deficiencies could be expected.

Section 5 – Inspection: This section presents guidance on inspection of FRP-RSC bridge elements by explaining several types of available inspection methods, their applicability, and the inspection procedures.

Section 6 – Recordkeeping: This section presents guidance for collection and recordkeeping of data for inspection of FRP-RSC bridge elements.

1.5 REFERENCES

To some extent, the inspectors can use their knowledge and experience on the existing inspection manuals and guidelines developed for conventional reinforced concrete (RC) and prestressed concrete (PC) for assessment of FRP-RSC elements. This framework, specific to FRP-RSC elements, acts as a supplementary document to already available general purpose bridge inspection documents some of which are listed below:

- National Bridge Inspection Standards (23 CFR 650 Subpart C): https://www.fhwa.dot.gov/bridge/nbis.cfm
- Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's bridges (Report No. FHWA-PD-96-001): https://www.fhwa.dot.gov/bridge/mtguide.pdf
- U.S. DOT/FHWA - Specifications for the National Bridge Inventory (March 2022) (23 CFR 650.317(b)(1)): https://www.fhwa.dot.gov/bridge/snbi.cfm
- AASHTO - The Manual for Bridge Evaluation (23 CFR 650.317(a)(3)): https://www.regulations.gov/search?filter=fhwa-2017-0047-0274
- AASHTO - Manual for Bridge Element Inspection (23 CFR 650.317(a)(4)): https://www.regulations.gov/search?filter=fhwa-2017-0047-0273
- FHWA - Bridge Inspector's Reference Manual (23 CFR 650.305): https://www.fhwa.dot.gov/bridge/nbis/pubs/nhi23024.pdf

Inspectors should be aware that without proper FRP-specific procedures and guidance, there could be room for misinterpretation. Many of the serviceability issues related to conventional RC such as cracking, permeability, carbonation, chloride content and concrete cover may not pose the same concern for FRP-RSC elements. However, FRP-RSC may be prone to such problems as alkali and UV issues that are of no concern for conventional RC. Hence the inspectors and inspector trainees should familiarize themselves with the first four sections of the framework which will serve as foundation for understanding the peculiarities of the FRP composites.

SECTION 2 BACKGROUND

2.1 FRP COMPOSITES

Fiber-reinforced polymers (FRPs) are composite materials consisting of reinforcing fibers impregnated with polymeric resins. While the fibers provide the load bearing action, the polymeric matrix (or polymeric resin) gives a desired geometry and transfers the forces to the fibers. The matrix also prevents fibers from buckling and protects it from degrading environment such as humidity or abrasion.

2.1.1 Historical Perspective

The 1930s was a significant decade for the history of FRP composites. It was during this period that the necessary components, including fibers and matrices, started to come together for the production of FRP composites. In 1932, Owens-Illinois accidentally invented the mass production of glass fibers by directing the jet of compressed air at a stream of molten glass. Later, in 1935, Owens-Illinois partnered with Corning Glass to create the first patented fiberglass. Subsequently, in 1938, DuPont developed and patented the first polyester resin, which was a suitable material for the production of fiber composites. Hence, the 1930s marked the beginning of the FRP industry since the fibers and resins created during that period remain the primary components used in manufacturing FRP composites today.

In the 1940s, during World War II, the FRP industry progressed from laboratory research to actual production. The need for lightweight and strong composites during the war led to significant advancements in the FRP industry. In 1942, the Pittsburgh Plate Glass Company produced the first fiberglass laminates using low-pressure polyester resins for the manufacturing of aircraft, boats, and automobile parts. However, during the 1950s and 1960s, the application of FRP composites remained largely limited to the military and aerospace industry, despite the continued advancements and innovations in manufacturing technologies.

One of the first civil engineering applications of FRP composites was a dome constructed in Benghazi, Libya in 1968. Similarly, the first FRP bridge designed for pedestrian use was built in Israel in 1975. However, early research on the use of FRP composites for the strengthening and repair of various structural members was primarily concentrated in Japan, Switzerland, and Germany from the late 1970s to the early 1980s. The use of FRP materials for retrofitting concrete structures was first documented in Germany in 1978. Research on exploring the use of FRP composites in the repair and retrofitting of civil infrastructure began in Japan in the early 1980s, with the first composite repair application performed in 1984 when cracks in railway bridge piers were repaired with carbon fiber sheets. In Europe, one of the first field applications of FRP strengthening was performed on the Ibach Bridge in Lucerne, Switzerland in 1991. The United States and Canada began their research and application of strengthening with FRP composites in the late 1980s, lagging behind Japan and Europe by almost a decade. The first precast post-tensioned bridge in the US that used three different materials, GFRP, CFRP, and steel cables, to prestress a deck slab was built in Rapid City, South Dakota, in 1991. Since then, various research studies have been conducted in North America to explore the possible applications of FRP composites in civil engineering.

2.1.2 Reinforcing Fibers

There are mainly three types of fibers used for bridge construction: glass, carbon, and aramid fibers. In the recent years, basalt fibers have been proposed as an alternative to glass fibers. Depending on the type of fibers used, the FRP composites are termed as GFRP, CFRP, AFRP, and BFRP for glass, carbon, aramid, and basalt fibers respectively.

2.1.3 Matrices

The basic types of polymers that can be used as matrices in FRPs are thermoplastics and thermosets (e.g., epoxies, polyesters, and vinyl esters), with thermosets being used more commonly. The main difference between these two types of resins is that thermoplastics can be reheated for bending without damage to the matrix while thermosets cannot be bent under heat once cured. Different additives and fillers can also be mixed with polymeric resin to improve performance, tailor composite performance, and reduce costs. Figure 1 shows the composition of FRP composites typically used in bridge application.

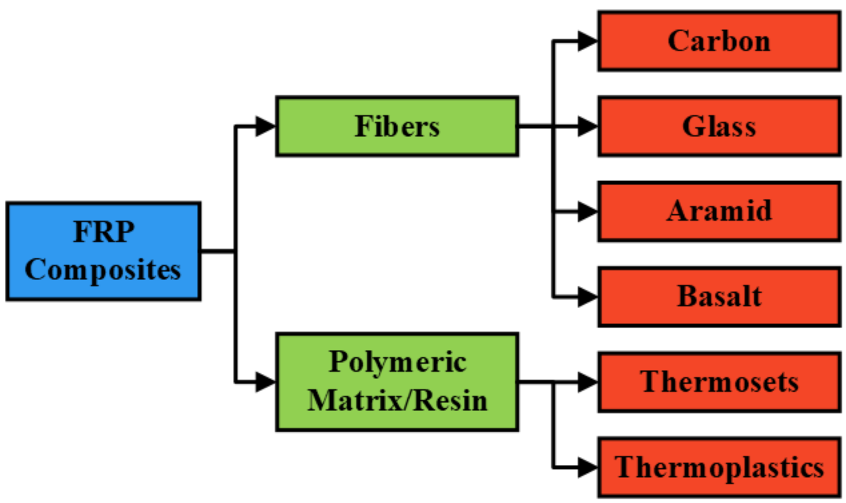


Figure 1 Composition of FRP composites used in bridge application (Source: Authors)

2.2 MANUFACTURING OF FRP COMPOSITES FOR CIVIL ENGINEERING APPLICATIONS

The reinforcing fibers are available in the form of strands/tows, yarns, and roving when it arrives at the manufacturing facility of the FRP composites. Apart from being available as continuous fibers (long fibers), reinforcing fibers are also available in the form of discontinuous fibers (short or chopped fibers). The reinforcing fibers can be either used directly or they can be first transformed into textile or fabric products such as nonwoven fabrics, unidirectional (UD) fabrics, and woven fabrics for manufacturing of FRP composites. In general, the manufacture of FRP composites involves building up layers of resin impregnated fibers and fabrics via successive wetting and curing process.

2.2.1 Available FRP Products

The FRP composites to be used for civil engineering applications are fabricated into a variety of structural forms such as laminates (wraps/sheets, strips, and plates), bars (rods), cables (strands), grids, structural shapes, and decks. The FRP laminates can be categorized as wet layup, prepreg, and precured systems, depending upon where or when the dry sheets of fibers are saturated with resin. FRP laminates are the most common forms of FRP composites that are used in externally bonded FRP systems for strengthening existing structures. Similarly, FRP rebars are commonly used in concrete elements as structural reinforcements for new construction. Based on the methods used to establish bond between the rebars and the concrete by creating variations in the geometry of their cross section and surface, FRP bars can be categorized as helically wrapped (HW), sand coated (SC), helically wrapped sand coated (HWSC), indented (In), or ribbed (Rb).

2.2.2 Manufacturing Methods

2.2.2.1 Hand Lay-Up Method

The hand lay-up method, also referred as wet lay-up process, is the most commonly used method for fabricating as well as applying FRP composite laminates to other surfaces. The general steps involved in a hand lay-up method are preparing mold/substrate, applying resin, lay-up of reinforcing fibers, reapplying resin, consolidation, and repeating the previous 3 steps, and finally curing.

2.2.2.2 Pultrusion

Pultrusion, derived from the words “pull” and “extrusion”, is the process of manufacturing continuous lengths of FRP composites (laminates, bars, structural shapes, cables) by pulling continuous reinforcing fibers or fiber fabrics through a resin bath and curing them into desired shapes of constant cross section. The schematic diagram of the steps involved in a pultrusion process is shown in Figure 3. The FRP rebars and precured laminates for externally bonded applications (as shown in Figure 2) are manufactured by using this method.

2.3 APPLICATION OF FRP IN CONCRETE BRIDGE ELEMENTS

There has been significant growth in the use of FRP composites in concrete bridges over the last decades as shown in Figure 4. They have been used for new construction or rehabilitation of existing bridges. FRP applications in concrete bridge elements can be subdivided into two main categories; FRP bars, rods, and strands as an internal reinforcement; and FRP sheets, wraps, and near-surface mounted (NSM) FRP bars as external reinforcement as shown in Figure 5.

1. Removal of dust, dirt and laitance from the substrate (Hydroblasting)

2. Application of resin on FRP and substrate

3. Application of FRP on substrate

4. Application of pressure onto the applied FRP

Figure 2 Precured laminate method (Carmichael and Barnes 2005)

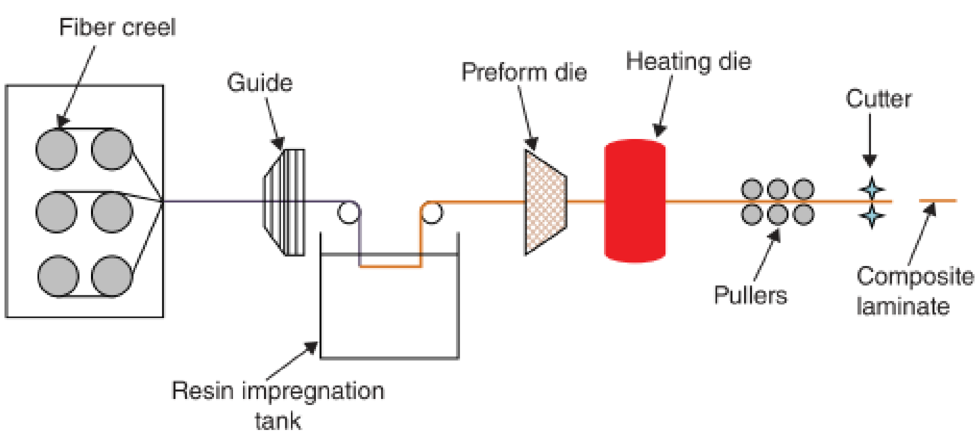


Figure 3 Pultrusion method (Biswas and Anurag 2020)

Figure 4 Types of FRP application (Khedmatgozar Dolati et al. 2022)

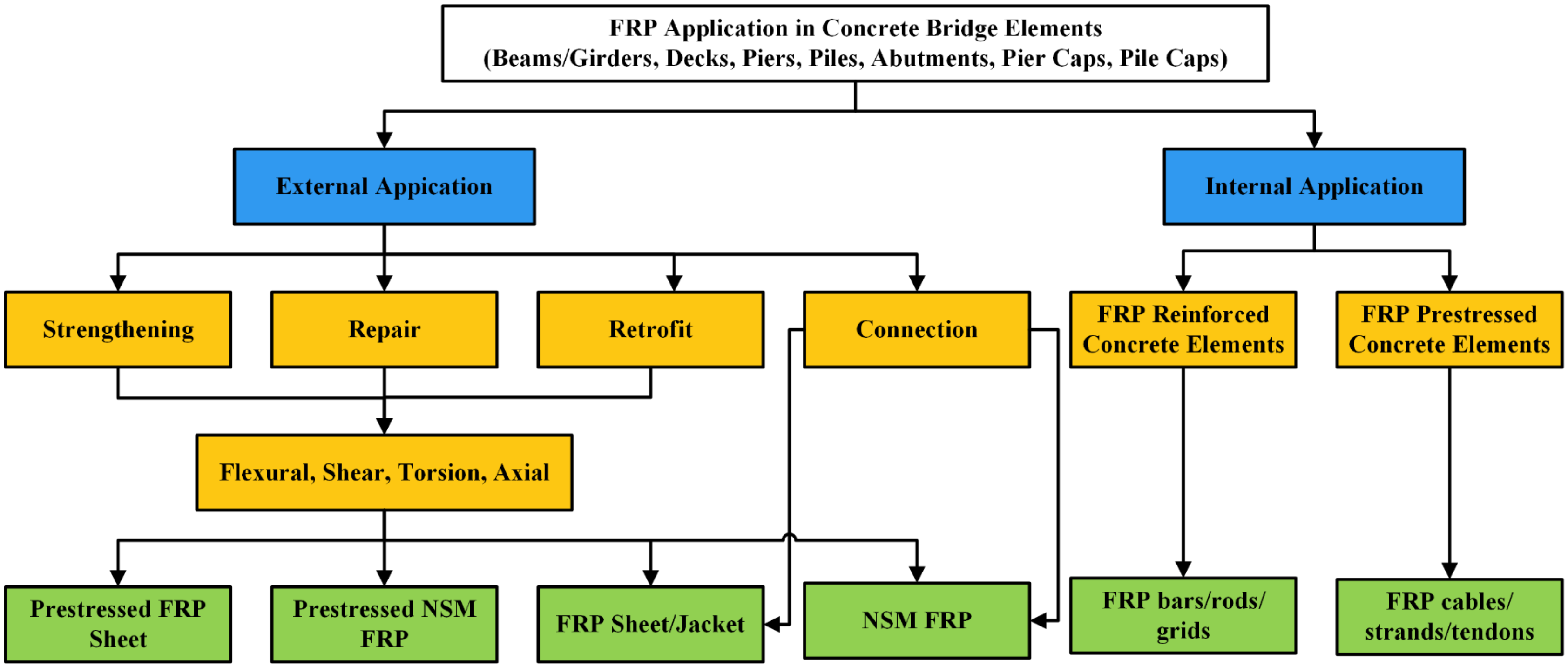


Figure 5 FRP application in concrete bridge elements (Source: Authors)

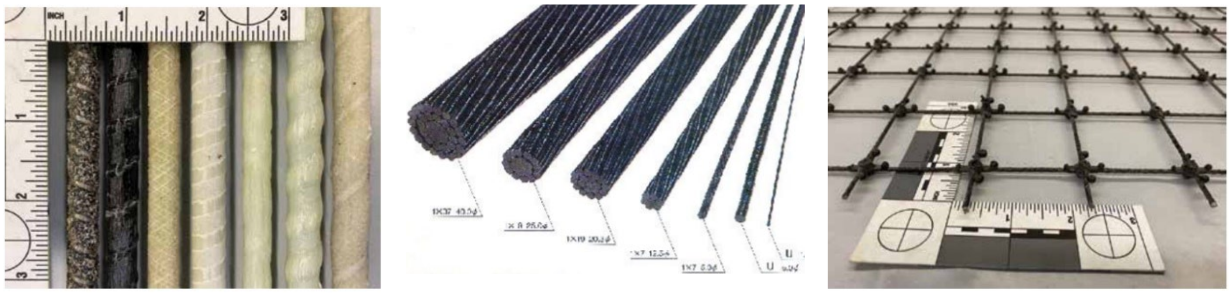
2.3.1 FRP Strengthened Bridge Elements (External Application)

Design and construction errors, accidental impacts, natural disasters, changes in functionality, and aging result in the need to repair, strengthen, or retrofit structural elements. The term "repair" refers to when the FRP composites are applied to correct a structural or functional deficiency, "strengthening" refers to situations when the application or addition of FRP improves the performance of existing elements (e.g., to meet the upgraded design code), and when FRP composites are implemented to upgrade the seismic performance of an element, the term “retrofit” is employed. The most common techniques for FRP strengthening are externally bonded FRP fabrics and pre-cured laminates applied to concrete surfaces using adhesive materials such as epoxy resins as shown in Figure 6. The integration of FRP composites with the existing concrete substrate enhances the capacity of structural elements by acting as external reinforcement.

Figure 6 FRP strengthened bridge girders (Carmichael and Barnes 2005)

2.3.2 FRP Reinforced Bridge Elements (Internal Application)

FRP rebars are alternatives to steel, stainless steel, and epoxy-coated steel bars in reinforced concrete applications when durability, electromagnetic transparency, or ease of demolition in temporary applications is essential for the project. GFRP bars are now used worldwide in tunnelling applications where the TBM (Tunnel Boring Machine) has to enter the retaining wall through a soft-eye. FRP bars, strands, and, more recently, meshes (Figure 7) have been successfully implemented as structural reinforcement for concrete members in bridge and building projects in the past three decades. Glass/vinyl-ester FRP bars are the most commonly used FRP bars for internal application. Figure 8 shows a fully FRP reinforced concrete bridge project located at the 23rd Avenue over Ibis Waterway, Broward County, FL, USA.



a) FRP bars b) FRP strands c) FRP mesh (grid)

Figure 7 FRP materials applicable for internal reinforcement of concrete members (Khedmatgozar Dolati et al. 2022)

Figure 8 The use of FRP reinforcing bars for piers and bent caps (Broward County, FL, USA) (Ekenel, y Basalo, and Nanni 2021)

SECTION 3 FRP DESIGN AND INSTALLATION PRACTICES

3.1 STANDARDS AND DESIGN SPECIFICATIONS (SERVICEABILITY CRITERIA-LIMIT STATE)

When designing a concrete element using FRP composites either as reinforcement or strengthening system, the guidelines set forth in the American Association of State Highway and Transportation Officials (AASHTO) design specifications should be used with additional specifications per the specific state DOT. AASHTO specifications provide detailed information on the materials, testing procedures, and design methods for the use of FRP composites in bridge construction. Several organizations have developed guidelines for the design of reinforced concrete structures with FRP composites, including AASHTO, the American Concrete Institute (ACI), the Canadian Standards Association (CSA), and the Japan Prestressed Concrete Institute (JPCI).

3.1.1 External Application

The design for repairing and strengthening highway bridge structures with externally bonded FRP composites systems is established by the Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements, 2nd Edition (AASHTO 2023)[1]. This guideline discusses two main types of externally bonded FRP systems: dry fiber-fabric sheets saturated with epoxy resin (e.g., wet lay-up and prepreg systems) and precured laminates (e.g., near-surface mounted (NSM) FRP systems). Surface preparation is essential before applying any strengthening system, and addressing existing steel reinforcement corrosion is crucial since FRP systems do not halt ongoing corrosion.

FRP retrofitting has proven effective in strengthening bridge structures against various types of loads, including static, quasi-static, and dynamic forces. It has been successfully employed for flexural, shear, and axial strengthening of concrete elements, enhancing their ductility and load-carrying capacity. The design approach involves using a resistance factor determined by the structural application, applied to the nominal capacity to establish the factored capacity for design. Additionally, the strength reduction factor for FRP systems influences the structural member's nominal capacity based on the stress in the FRP material. Environmental factors are also considered to account for long-term durability.

To prevent sudden member failure in case of FRP system damage, strengthening limits are imposed. These limits aim to ensure that a loss of FRP reinforcement does not lead to catastrophic structural failure. The guidelines emphasize retaining a substantial portion of the original factored capacity (excluding the strengthening system) in the strengthened member. Specific restrictions are placed on the factored capacity of FRP-strengthened structures to address fire safety concerns. The stress levels in FRP materials during service loads are governed by their creep rupture properties and fatigue resistance. While the FRP's contribution to deflections in flexural members

[1] Use of AASHTO Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements. 2nd ed. (2023) is not a Federal requirement.

within the service range is typically minimal, it becomes significant in the inelastic range after the primary steel reinforcement has yielded (ultimate condition).

3.1.2 Internal Application

The design and construction of structural concrete bridge members reinforced with GFRP bars should follow the latest version of the AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete (AASHTO 2018)[2]. The use of fiber types other than glass, such as carbon, basalt, and aramid fibers are not covered in the specification. Any provisions not explicitly named in the guide can follow the AASHTO LRFD Bridge Design Specifications (AASHTO 2020)[3]. The GFRP rebars should meet all material specifications set forth by both the respective state DOT and the ASTM D7957 (ASTM D7957/D7957M 2017)[4] , "Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement". A new ASTM specification, ASTM D8505, "Standard Specification for Basalt and Glass Fiber Reinforced Polymer (FRP) Bars for Concrete Reinforcement" (ASTM D8505/D8505M-23 2023)[5] for BFRP and GFRP rebars was issued in 2023 addressing the second generation of rebars with a minimum modulus of elasticity of 8,700 ksi. Although the inspection of FRP-PC (FRP prestressed concrete) is not covered in this version of the guide, AASHTO issued the 1st edition of the Guide Specifications for the Design of Concrete Bridge Beams Prestressed with Carbon Fiber-Reinforced Polymer (CFRP) Systems in 2018.

Given the brittle behavior of both FRP reinforcement and concrete; compression- and tension-controlled sections are acceptable in the design of flexural members reinforced with FRP bars. The strength reduction factor ranges from 0.75 to 0.55, for compression-controlled to tension-controlled, respectively. This is different from steel-RC design where the compression-controlled sections have a lower strength reduction factor (0.75) compared to tension-controlled sections (0.90). Additionally, FRP-reinforced concrete members have lower stiffness after cracking and are more sensitive to deflection due to the variable stiffness, brittle-elastic nature, and bond features of the FRP composite. As a result, serviceability limit states like deflection and crack width often govern the design of FRP-RC elements instead of the design for flexural strength. One effective approach to address this is by designing for a compression-controlled section (concrete crushing failure before tensile rupture of the FRP rebar).

FRP rebars do not corrode like steel rebars. However, they can deteriorate under harsh environmental conditions, which can limit the service life of the structure. Unlike steel-RC structures, deterioration of FRP rebar does not lead to cracking or spalling of the concrete cover. Therefore, some design criteria for corrosion control in steel-RC structures are not applicable to or necessary for FRP-RC structures. The absence of warning signs for failure of FRP-RC elements

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[2] Use of AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete. 2nd ed. (2018) is not a Federeal requirement.

[3] Use of AASHTO LRFD Bridge Design Specifications. 9th ed. (2020) is not a Federeal requirement.

[4] Use of ASTM D7957/D7957M Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement (2017) is not a Federal requirement.

[5] ASTM D8505/D8505M-23 Standard Specification for Basalt and Glass Fiber Reinforced Polymer (FRP) Bars for Concrete Reinforcement (2023) is not a Federal requirement.

when exposed to harsh environmental conditions is considered a deficiency because of the brittle failure characteristic of FRP. Therefore, design guides for FRP-RC include an environmental reduction factor on the design tensile strength of FRP bars to account for the long-term effects of environmental exposure. This factor ranges from 0.7 to 0.8 in the AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete Specifications. The maximum crack width for FRP reinforced concrete is limited to 0.028 inches to address concerns related to durability and ensure an acceptable appearance (compared to 0.017 inches in steel-RC beams). A stress at service limit is set for GFRP-RC elements to control cracks.

Due to glass transition temperature inherent to polymers, elevated temperatures can cause severe degradation of FRP composite properties. For this and other considerations, AASHTO specifies a minimum concrete cover for GFRP bars ranging from 1.0 to 2.0 times the bar diameter for all exposure conditions except for additional fire protection, without any additional suggestion on the latter. However, if GFRP bars are well anchored outside of the area directly exposed to fire, they can retain considerable strength and stiffness during a fire event.

To prevent GFRP reinforcing bars from failing due to creep, the sustained stress should not exceed the creep rupture stress, and the maximum sustained tensile stress in the FRP reinforcement should be less than the design tensile strength of FRP bars multiplied by a creep rupture reduction factor of 0.30. The contribution of GFRP bars as compression reinforcement should not be accounted for.

3.2 CONSTRUCTION SPECIFICATIONS/INSTALLATION PRACTICES

3.2.1 External Application

The external application is focused on strengthening, retrofitting, or repair of a reinforced concrete element usually with reinforcing steel. Different applications could be used to improve the capacity and performance of the RC element. The typical method for strengthening concrete elements involves the use of externally bonded FRP sheets or jackets, which consist of one or more layers of FRP applied to the concrete surface. The application of these sheets/jackets involve an assessment of the base material and surface preparation.

According to the Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements (AASHTO 2023)[1] the installation procedures for FRP systems can vary between different manufacturers. However, the guide identifies two commonly used systems: wet-layup, which involves the use of dry fiber-fabric sheets saturated with epoxy resin, and precured fiber/resin laminates that are bonded to the concrete surface with an adhesive resin.

To ensure proper bonding between the concrete surface and the FRP system, the concrete surface should be dry and possess an open pore structure. A minimum concrete surface profile (CSP) is 3 on a CSP rating scale of 1 – 10, a very rough surface will have a CSP of 10 and very smooth surface be a CSP 1, as suggested by International Concrete Repair Institute (ICRI) in ICRI 310.2, “Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, Polymer Overlays, and Concrete Repair”, and illustrated in ICRI PC1-10, “Concrete Surface Profile Chip Set”. Out-of-plane variations, such as form lines, should not exceed 1/32 inch or the tolerances suggested by the manufacturer. All bond inhibiting materials should be removed from the surface prior to the application of FRP. Any holes or voids should be filled with compatible epoxy paste. To minimize stress concentrations in the FRP, rounding the corners of the concrete elements where fibers are wrapped is used.

3.2.2 Internal Application

The AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete (AASHTO 2018)[2] provides construction specifications for cast-in-place structural elements. The guide emphasizes the importance of handling GFRP rebars with care during delivery, storage, and handling to avoid bending, coating with harmful materials, dropping, dragging, or exposing them to temperatures above 120 °F. Proper construction practices and resin additives can reduce exposure to ultraviolet rays. Before being placed in concrete, FRP bars should be protected from direct sunlight and moisture.

To ensure proper bonding with the surrounding concrete, GFRP rebars should be free of harmful materials and firmly in place. The use of steel tie wires, bar chairs, supports, or clips coated with epoxy or plastic is allowed to prevent displacement and maintain cover distances. A minimum concrete cover for GFRP rebars should range from 1.0 to 2.5 inches, depending on the RC element.

If bent bars are used, they should be manufactured with the desired bends. Field bending is not possible, and factory-formed bends should meet minimum inside bend diameter. All construction details should be shown on project drawings. GFRP rebars should not be cut in the field using shear or flame cutting. In general, installation procedures are similar to those for steel rebars, with specific provisions outlined in the guide specifications (AASHTO 2018)[2].

SECTION 4 DEFICIENCIES IN FRP APPLICATION

4.1 DEFICIENCIES IN FRP STRENGTHENED BRIDGE ELEMENTS (EXTERNAL APPLICATION)

The deficiencies in external application of FRP can be found in: A. FRP, B. FRP-adhesive interface, C. Adhesive, D. Adhesive-concrete Interface, E. Concrete, and F. Concrete-reinforcement interface as shown in Figure 9 and Table 1. Based on the location, all the deficiencies in external application are broadly classified under three different categories: FRP composite defects, bond defects, and defects in concrete.

Table 1. Classification of deficiencies in external FRP application

Defect Categories	Defect Locations	Defects
FRP Composite Defects	A. FRP	A.1-A.5. Surface Defects (A.1 Blisters, A.2 Wrinkling, A.3 Scratches, A.4 Discoloration, A.5 Fiber Exposure)
		A.6. Voids in FRP
		A.7/A.8. Debonding/Delamination in FRP
		A.9/A.10. Cracks/Impact Damage in FRP
Bond Defects	B. FRP-Adhesive Interface	B.1. FRP-Adhesive Debonding
	C. Adhesive	C.1. Voids in Adhesive
	D. Adhesive-Concrete Interface	D.1. Adhesive-Concrete Debonding
Defects in Concrete	E. Concrete	E.1 Cracks in Concrete
		E.2. Voids in Concrete
		E.3 Delamination/Spalling in Concrete
	F. Concrete-Reinforcement Interface/ The Plane Passing Through the Reinforcement Layer	F.1 Cover Separation F.2 Corrosion in Steel Reinforcement F.3 Concrete-Reinforcement Debonding

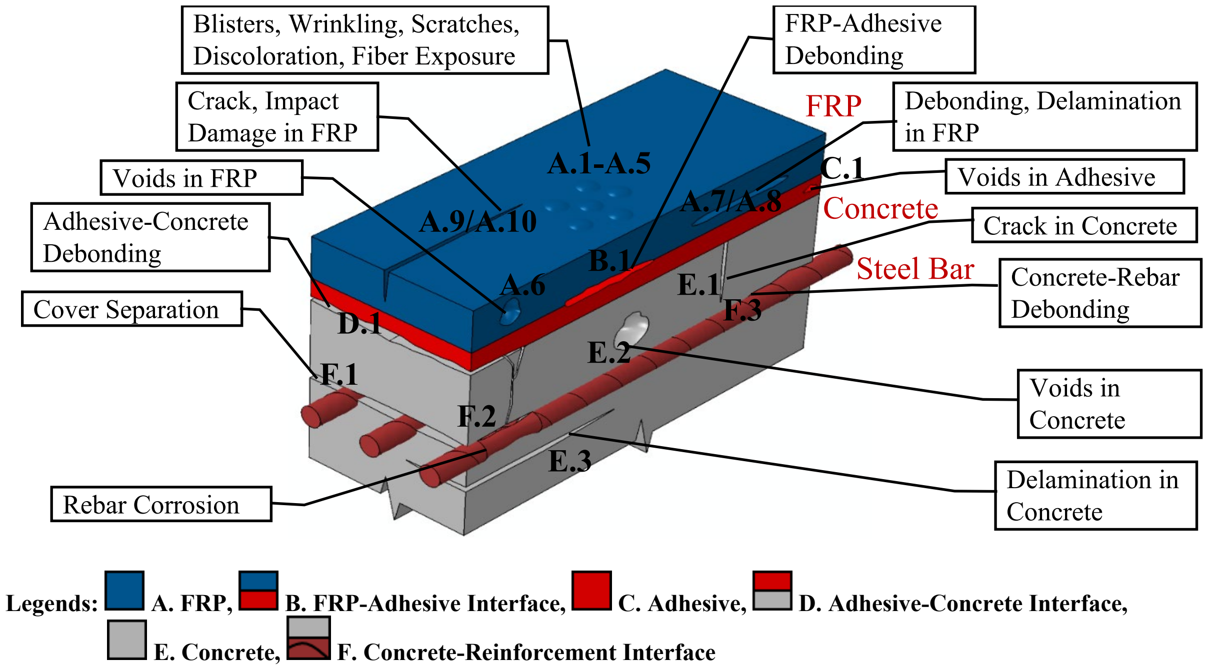


Figure 9 Deficiencies in external FRP application (Source: Authors)

4.1.1 FRP Composite Deficiencies

A.1 Blisters

Blisters are bubble-like formations that occur on the surfaces of externally applied FRP composites as shown in Figure 10. These appear due to the combined action of freeze-thaw cycles and entrapped moisture at contact between the substrate and the FRP material or at the inter-laminar interfaces of the composites. Nevertheless, because its effects are primarily restricted to the surface, this imperfection has little impact on the structural performance of the structure.

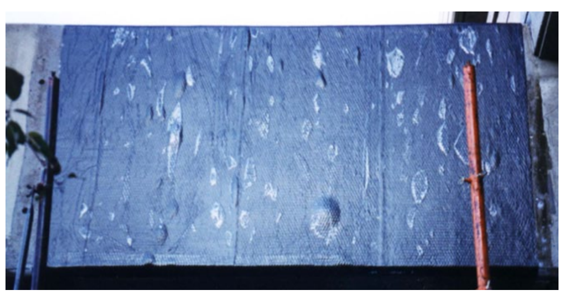


Figure 10 Blistering in FRP (Source: Authors)

A.2 Wrinkling

Wrinkling appears as creases or folds on the surface of the FRP composites (Figure 11), often occurring at corners and curves of the structure. It is caused by improper installation practices during the hand lay-up process, such as excessive stretching or shearing of the fabric. The safety of the structure may be compromised if it results in insufficient surface contact of the FRP composites with the substrate.

Figure 11 Wrinkling (Source: Authors)

A.3 Scratches

Scratches at the surface of externally applied FRP range from superficial scratches to deeper grooves (Figure 12). They can occur anytime during the installation and service life of the structure. They are detrimental if they develop into full-depth cracks as they propagate deep into the fibers of the composite.

Figure 12 Scratch caused at the externally applied FRP (Source: FHWA)

A.4 Discoloration

Discoloration (Figure 13) is mainly caused by exposure to UV rays, heat, chemicals, fire, excessive strain, subsurface defects, voids, and moisture penetration. It may be a sign of composite degradation, which may be followed by cracks and embrittlement.

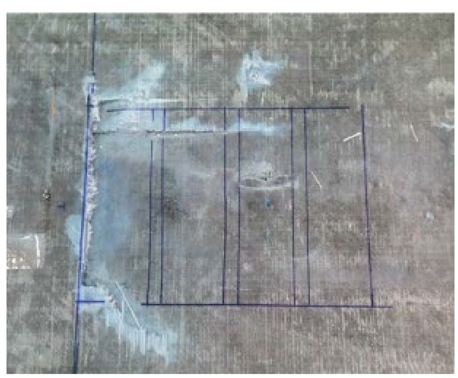


Figure 13 Discoloration (Telang et al. 2006)

A.5 Fiber exposure

Fiber exposure, as shown in Figure 14, are simply exposed fibers of the FRP composite caused mainly by improper handling and installation of FRP composites. These are the entry points of moisture and contamination into the composite which deteriorates the composite properties.

Figure 14 Fiber exposure (Telang et al. 2006)

A.6 Voids: fiber-matrix interface

Voids present at the fiber-matrix interface, as shown in Figure 15, are the cavities formed due to entrapped air within the layers of the composites. These are caused by overlapping of the fabrics during fabrication or installation. FRP composites with voids are the results of bad workmanship which reduces their laminar shear strength. The fabric/matrix defects are only related to precured laminates externally bonded to concrete or FRP bars for NSM (Near Surface Mounted) installation. In these cases, the fiber/matrix defects can and should be identified by the QC (Quality Control) process of the manufacturer.

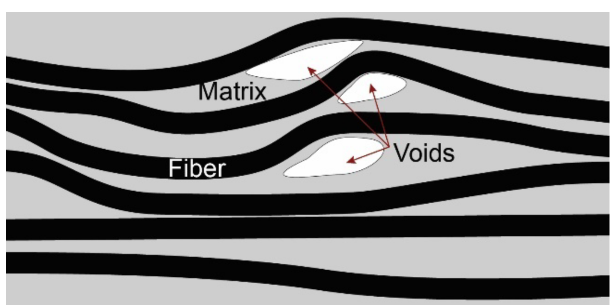


Figure 15 Voids inside composite material at the interlaminar interfaces (Source: Authors)

A.7 Fiber-matrix debonding

Debonding within FRP composites is the separation at the interface between the fiber and the matrix, as shown in Figure 16. It is mainly caused by the presence of surface moisture on the fibers. The effects of debonding include a loss of composite action, which reduces the material's ability to provide strength against transverse tension, inter-laminar shear, and impact.

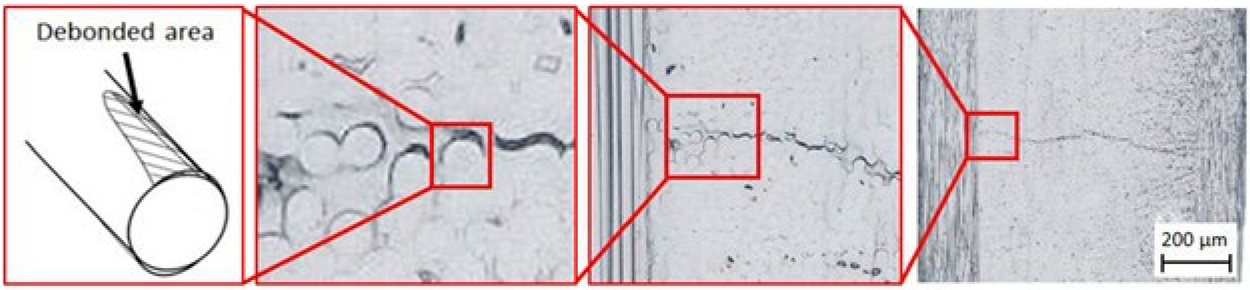


Figure 16 Debonding between fiber and matrix (Takahashi et al. 2022)

A.8 Delamination between composite layers

Delamination within FRP composites is the separation at the interface between the layers of FRP laminae comprising the composite as shown in Figure 17. It is often caused by moisture, foreign object contamination, and trapped air between the FRP layers. Delamination can lead to a loss of shear transfer capacity in the material.

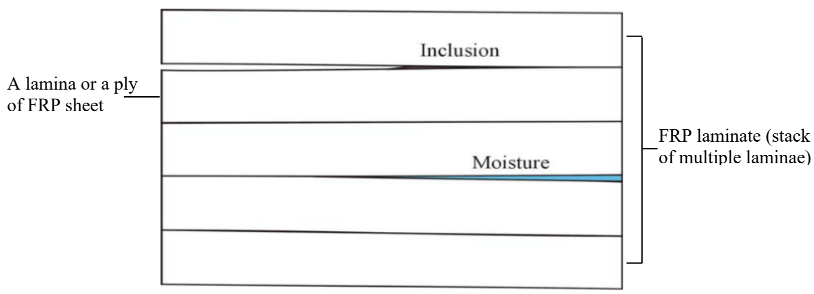


Figure 17 Delamination in FRP laminate (Karbhari et al. 2005)

A.9 Cracks

Cracks in FRP composites (Figure 18) mostly occur in the direction parallel to the fiber. They are caused by entrapped air, inadequate resin distribution, insufficient reinforcing fibers, impact, and service loads. Cracks may lead to failure if they propagate deeper and expand under loading conditions.

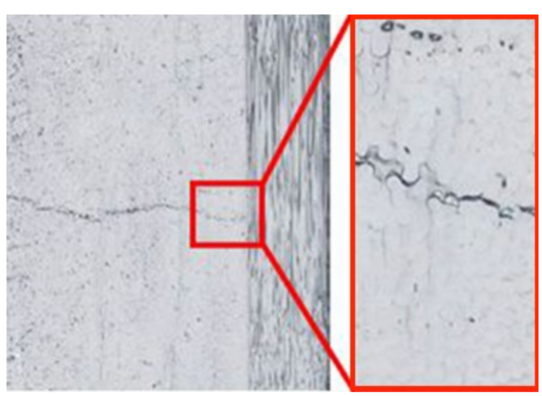


Figure 18 Crack formation in FRP composite (Takahashi et al. 2022)

A.10 Impact damage

Impact damage (Figure 19) is caused by moving objects. Slow-moving objects cause damage that is not critical at surface but significant at the internal level. Fast-moving objects cause damage at the surface level.

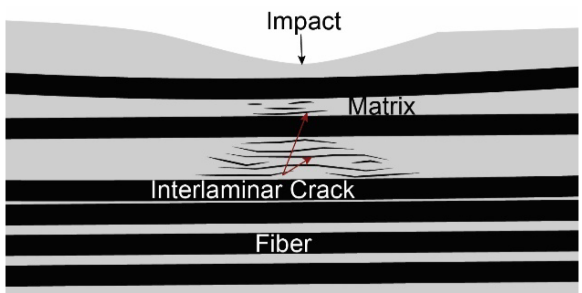


Figure 19 Damage at surface and subsurface due to impact (Source: Authors)

4.1.2 Bond Deficiencies

B.1/D.1 Debonding between FRP and concrete

Debonding (Figure 20) is the loss of cohesive and adhesive bond between the externally applied FRP and the concrete substrate. It can occur when flexural or shear cracks open under high loading conditions. It can be caused by improper installation practices, insufficient curing of resin, inadequate surface preparation, or surface moisture on the substrate. Excessive debonding may lead to brittle fracture of the concrete element underneath the external FRP as the composite fails to transfer the stresses to the substrate.

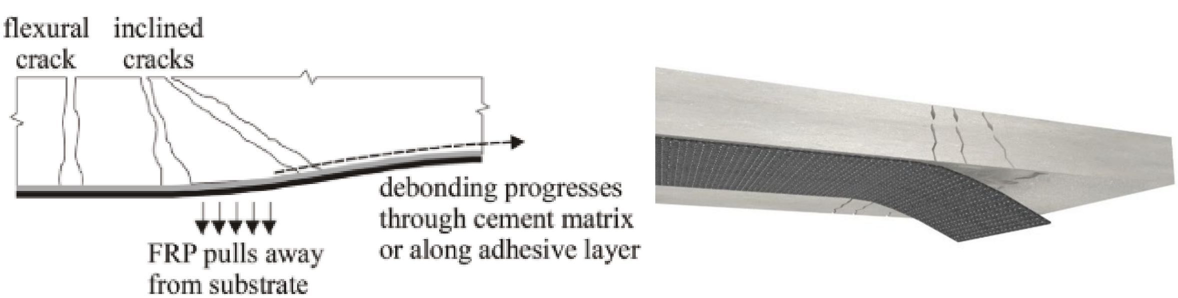


Figure 20 Debonding of externally bonded FRP (ACI 440.2R-17 2017)

B.2/C.1/D.2 Voids between FRP and concrete

Voids (Figure 21) are areas of zero contact between the FRP composites and the concrete substrate. They are typically formed due to air trapped in between the layers of composites, air mixed or volatiles contaminated or insufficient resin matrix, and irregular surface of the substrate. Voids can also form “bubbles” when moisture from the substrate evaporates and cannot escape prior to complete polymerization of the resin. Since voids cause regions of stress concentrations, it weakens the bond strength of the FRP application.

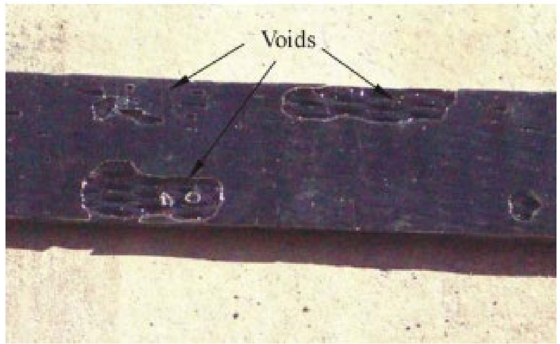


Figure 21 Voids at FRP-concrete interface (Karbhari et al. 2005)

4.1.3 Deficiencies in Concrete

E.1 Cracks

Cracks in concrete substrate are completely hidden behind the externally applied FRP. They are caused by shrinkage, thermal stresses, chemical exposure, weathering, corrosion of steel bars, design errors, poor detailing and construction practices and excessive loading conditions. Cracks are the points of entry for detrimental chemicals that attack steel reinforcement. Their presence in externally applied concrete elements weakens the bond between FRP and concrete (Figure 22).

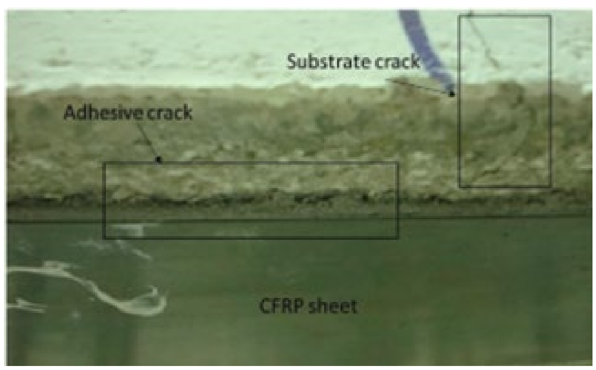


Figure 22 Cracks in concrete substrate (Malla et al. 2023)

E.2 Voids in concrete

The formation of voids in concrete is independent of the external application of FRP and related to the inadequate design and construction measures during the casting of the concrete substrate. Voids can form due to improper vibration of concrete during casting in addition to stiff or unworkable concrete, segregation, crowded rebar, insufficient concrete consolidation, and irregular aggregate sizing. It may cause concrete structures to deteriorate over time. Figure 23 shows voids formed on the surface of concrete.

Figure 23 Concrete voids (Source: Authors)

E.3 Concrete Delamination

Concrete substrate is weaker than the adhesive and the FRP used in an external application. Hence, delamination of concrete (Figure 24) occurs when the stresses and forces in FRP are high enough to rip out the concrete beneath it. It initiates near cracks or termination points of external FRP systems where the interfacial shear and normal stresses build up excessively. Delamination failures are sudden and brittle.

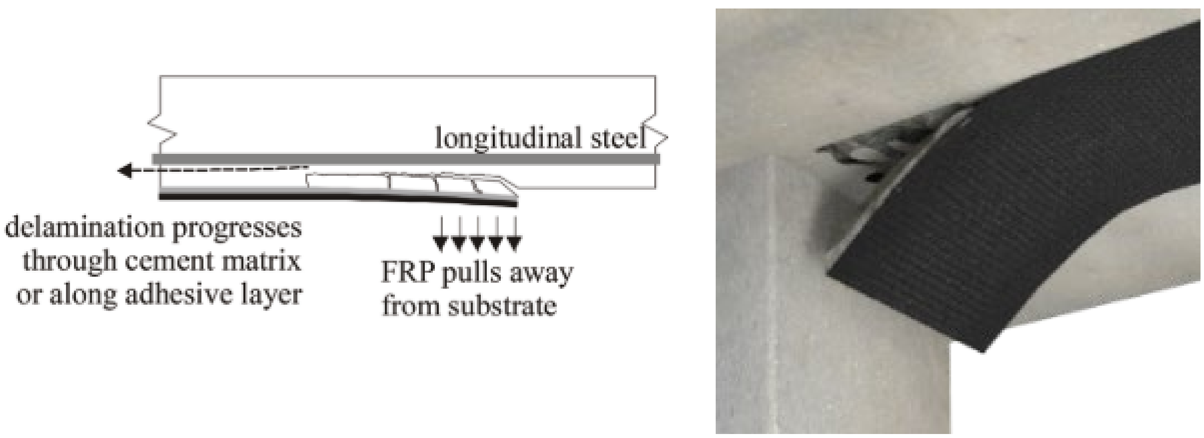


Figure 24 Concrete delamination (ACI 440.2R-17 2017)

F.1 Cover separation

While delamination occurs just beneath the externally applied FRP, cover separation (Figure 25) occurs at a deeper level up to the cover distance of internal reinforcement which provides a weaker horizontal plane for the separation to progress. Cover separation is also often referred to as FRP end peeling, concrete cover delamination, end-of-plate failure through concrete, concrete rip-off failure, debonding at rebar layer, and local shear failure. It occurs as the cracks that have reached up to the internal reinforcement begin to propagate horizontally along the level of reinforcement under high stresses in the presence of externally bonded FRP. Similar to delamination, it is a sudden and brittle failure.

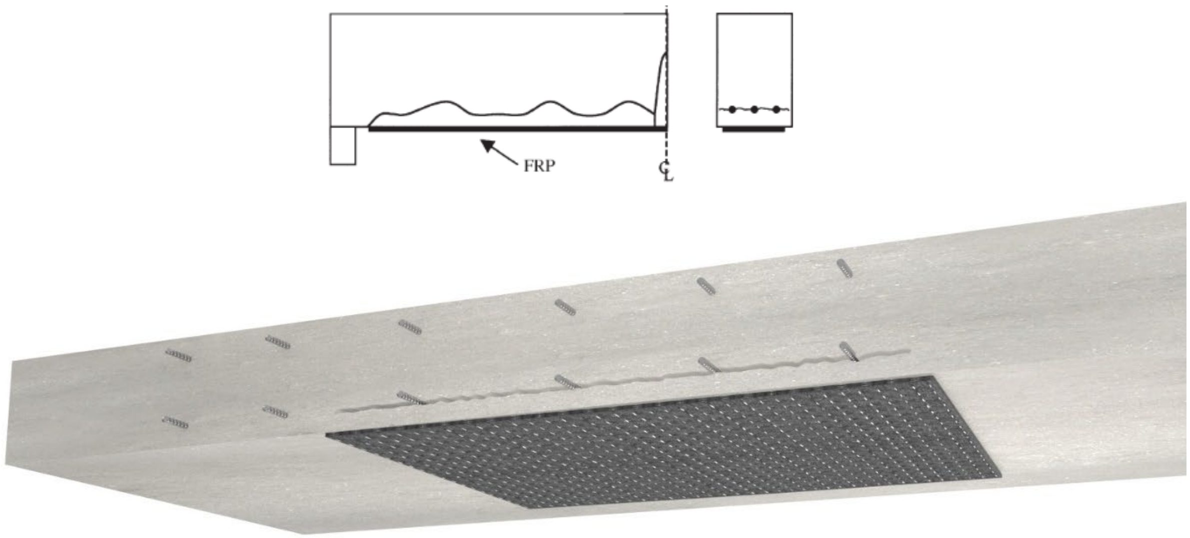


Figure 25 Cover separation (ACI 440.2R-17 2017)

F.2 Corrosion in steel reinforcement embedded in concrete substrate

External FRP is typically applied to strengthen steel reinforced concrete elements. The corrosion of steel reinforcement will not be completely stopped even though external FRP might decrease the rate of corrosion (Figure 26). Corrosion activity should be monitored on concrete elements even after strengthening measures have been applied.

Figure 26 Corrosion in steel reinforcement embedded in concrete substrate (Jung, Jeong, and Lee 2022)

4.2 DEFICIENCIES IN FRP REINFORCED BRIDGE ELEMENTS (INTERNAL APPLICATION)

In the case of internal application of FRP, the defects are possible at: G. FRP reinforcement, H. Concrete-FRP interface, and I. Concrete as shown in Figure 27 and Table 2. They are classified as: defects in FRP reinforcement, bond defects, and defects in concrete.

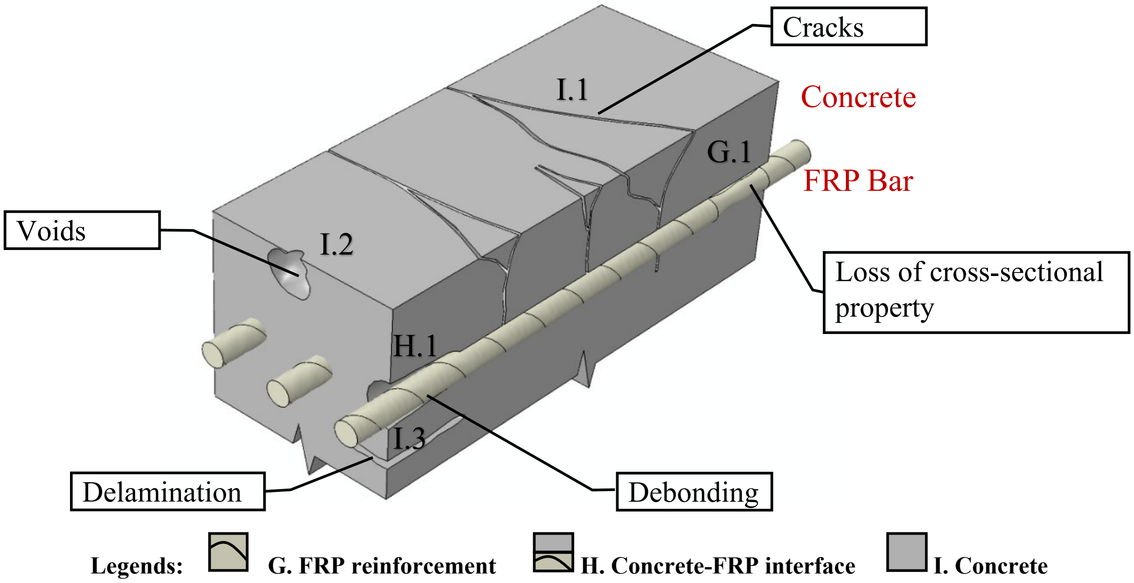


Figure 27 Potential deficiencies in internal FRP application (Source: Authors)

Table 2. Classification of potential deficiencies in internal FRP application

Defect Categories	Defect Locations	Defects
Defects in FRP reinforcement	G. FRP Reinforcement	G.1. Loss of Cross-sectional Property (Other Potential Defects: Voids at Fiber-Matrix Interface, Fiber-Matrix Debonding, Delamination Between Composite Layers, Fiber Exposure, Scratches, Cracks, Discoloration)
Bond Defects	H. Concrete-FRP Reinforcement Interface	H.1 Debonding (Others Potential Defects: H.2 Slippage)
Defects in Concrete	I. Concrete	I.1 Cracks I.2 Voids I.3 Delamination

4.2.1 Defects in FRP Reinforcement

Defects such as voids at fiber-matrix interface, fiber-matrix debonding, delamination between composite layers, fiber exposure, scratches, cracks, and discoloration can also occur in FRP rebars during manufacturing, transportation, storage and handling, and service.

G.1 Loss of Cross-Sectional Properties

The service life of FRP reinforced concrete members can be reduced due to chemical attacks of alkaline, saline, and other extreme environmental conditions. Degradation of FRP reinforcement due to chemical effects is a result of the corresponding degradation of the fibers and the matrix, as well as the fiber/matrix interface. There might not be visible or physical evidence of chemical attacks on FRP rebars embedded in concrete despite the reduction in their mechanical properties, which hinders the detection of the loss of cross-sectional physical and mechanical properties.

The available data mainly focuses on GFRP and BFRP bars for internal use, as well as CFRP laminates/sheets for external applications. However, due to variations in parameters and a lack of standardization, establishing clear degradation patterns, even for specific composites like GFRP/vinyl ester bars, can be challenging. Improvements in material properties over time also make earlier data less representative of modern FRP composites. Notably, alkaline exposure is identified as the most damaging condition, with CFRP displaying superior performance in aggressive environments, while GFRP exhibits resilience across various conditions. The environmental reduction factor available in the U.S. design guidelines account for the high pH level of both pore-water solutions and the presence of alkali ions, the mean temperature, and the humidity, for an assumed service life of 75–100 years (Benmokrane et al. 2020).

4.2.2 Bond Defects

H.1 Debonding

The structural performance of RC members primarily depends on the adequate bond between the concrete and the reinforcing bars. The bond ensures that the high tensile strength of the FRP rebars are used effectively. The tensile and the bond properties of the FRP rebars are of key importance for internal application in RC members. However, with the passage of time, the bond could gradually deteriorate due to environmental and load effects potentially resulting into bond failure of the FRP-RC members compromising the integrity of the structure.

H.2 Slippage

Slippage, a relative displacement between the reinforcing bars and the concrete, occurs when external forces overcome the strength of bond between them. Monitoring bond-slip is important because the structural integrity and overall strength of concrete structures depends on the condition and strength of the bond between the reinforcement and the concrete. Hence, more attention should be given to the detection and prediction of the occurrence of bond-slip to issue early warnings.

4.2.3 Defects in Concrete

The defects in concrete such as I.2 voids and I.3 delamination as described in external application (E.2, E.3) are the same whether FRP is used for strengthening or reinforcing purposes. However, the cracks in FRP-RC are discussed separately under this section as their formation is mostly associated with the difference in mechanical properties of FRP (low modulus of elasticity in FRP reinforcements) compared to steel.

I.1 Cracks

Cracks are the predominant defect reported by the bridge inspectors in the inspection of FRP-RC bridge decks as shown in Figure 28 and Figure 29, which can be attributed to the low modulus of elasticity of the FRP rebars. The initiation of cracks and large deflections in the concrete members reinforced with FRP rebars are one of the potential defects to be detected in internal application of FRP composites which raise serviceability concerns.

Figure 28 Top surface cracks in GFRP reinforced bridge deck (Shafei 2023)

Figure 29 Full depth crack in GFRP reinforced bridge deck (Shafei 2023)

4.3 DEFICIENCIES IN FRP-RSC ELEMENTS

All the deficiencies identified in the previous sections for both internal and external applications of FRP have been summarized in a comprehensive flowchart as shown in Figure 30.

4.4 POTENTIAL SOURCES OF DEFICIENCIES

The sources of deficiencies related to FRP composites and concrete are broadly divided into design factors, mechanical factors, environmental factors, and fabrication & workmanship errors. The presence of these sources would imply that deficiencies could be expected. The sources of deficiencies in FRP composites and the corresponding bond/interface defects shown in Figure 31 are covered in the following sections (Sections 4.4.1 to 4.4.4). However, for the source of deficiencies in concrete shown in Figure 32, a study by Mehrabi and Farhangdoust (2019) on the NDT methods applicable to health monitoring of accelerated bridge construction (ABC) closure joints can be consulted.

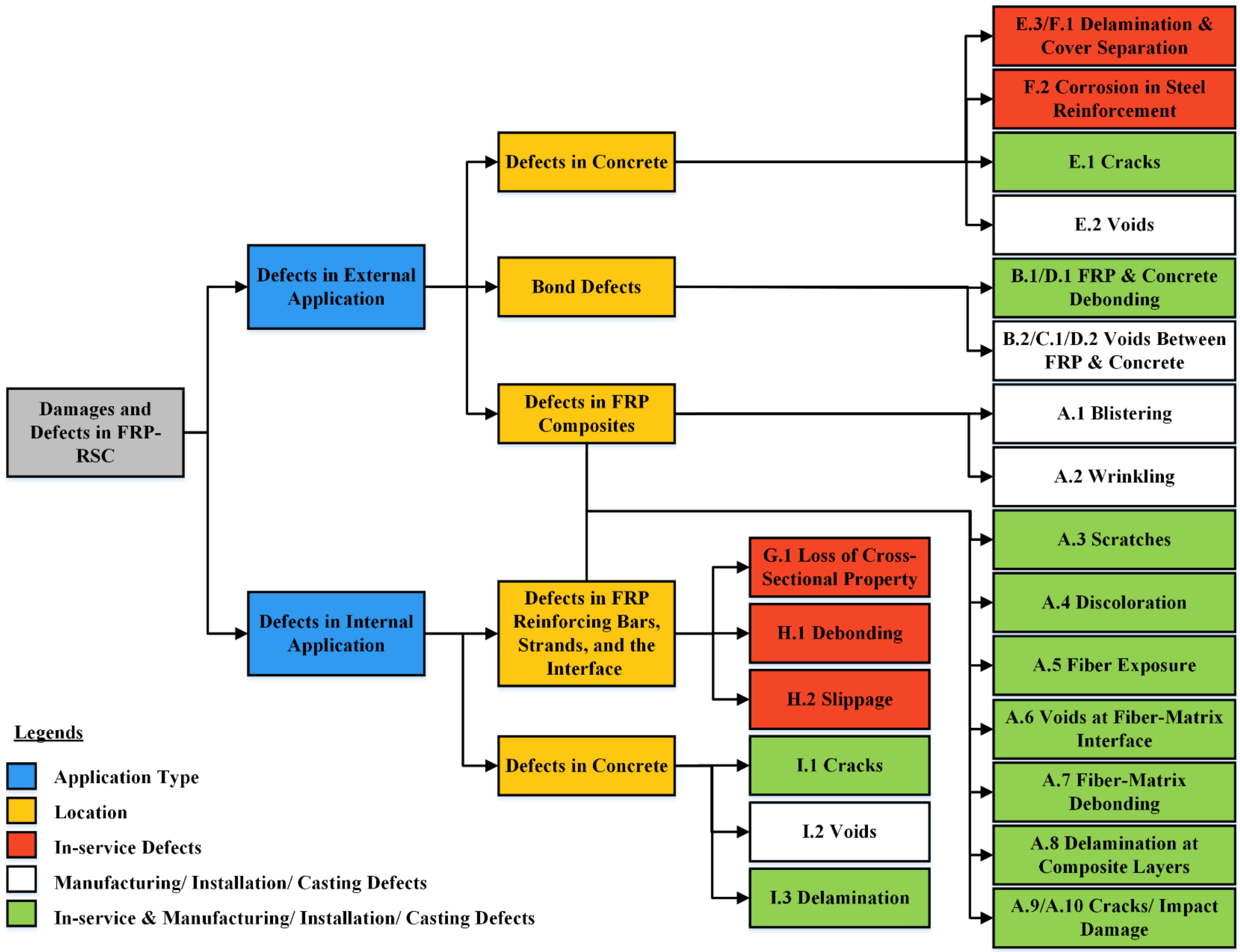


Figure 30 Deficiencies in FRP application (Source: Authors)

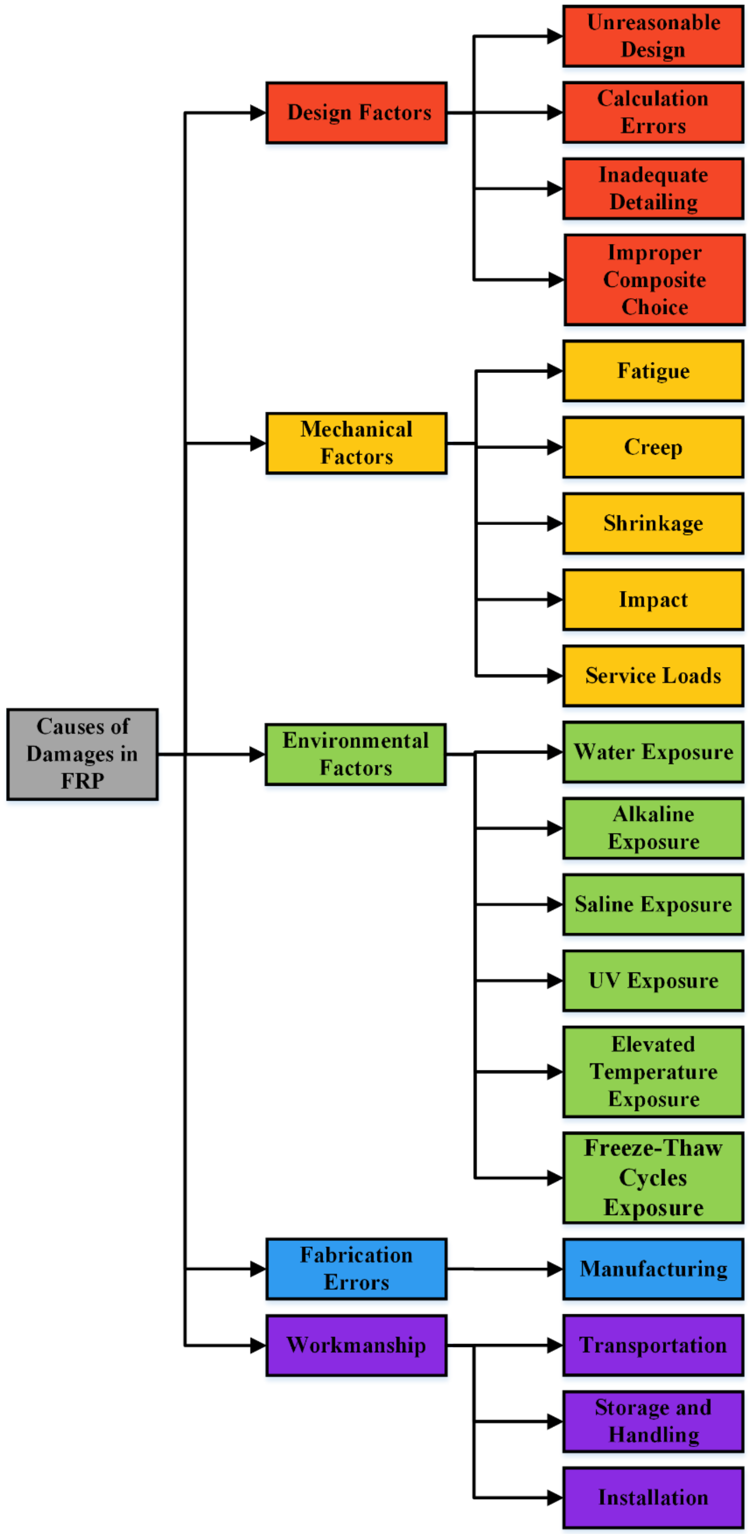


Figure 31 Sources of deficiency in FRP (Source: Authors)

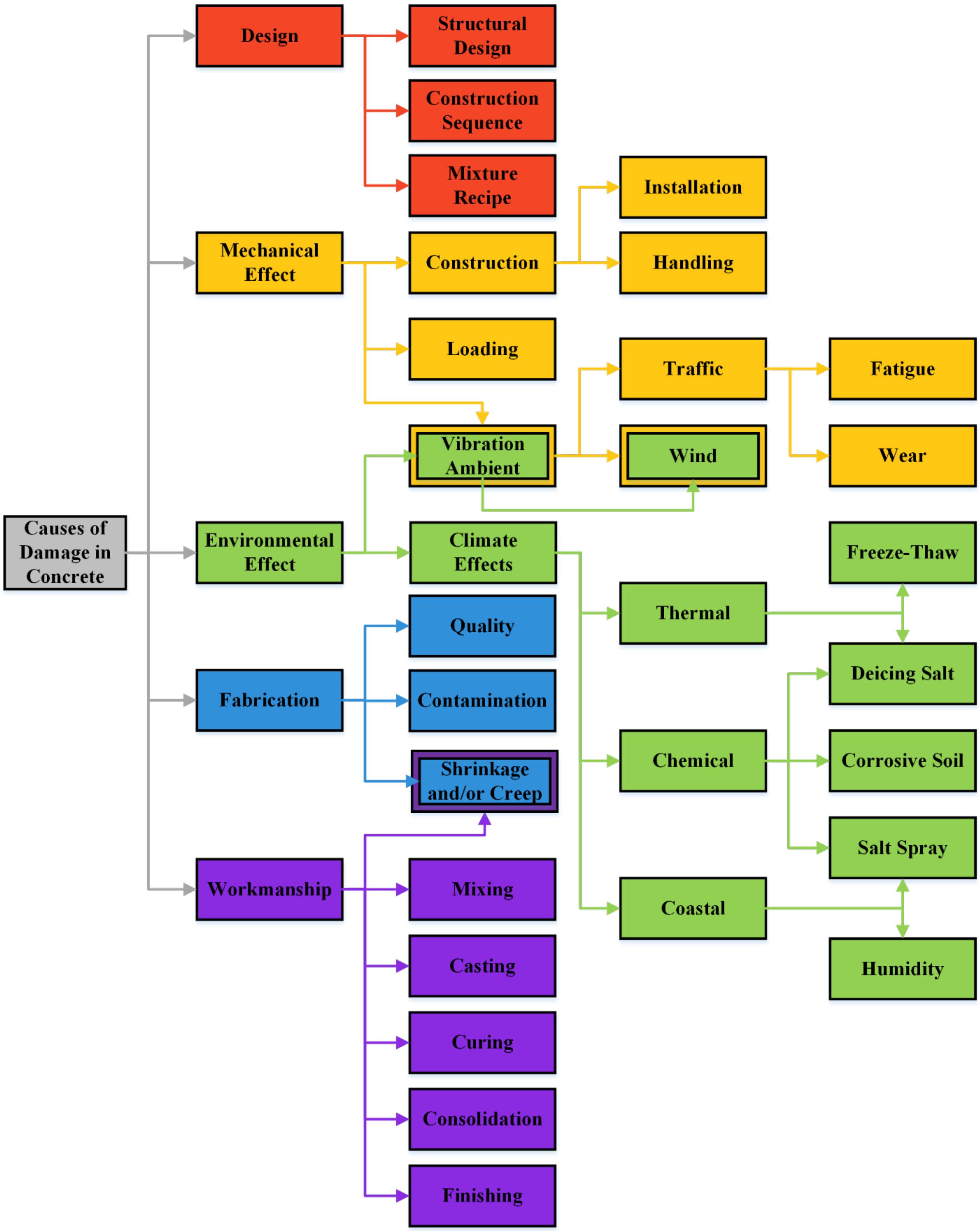


Figure 32 Sources of deficiency in concrete (Mehrabi and Farhangdoust 2019)

4.4.1 Design factors

The design factors causing defects in FRP application can be referred to as the deficiencies in the design process (can be lack of appropriate design specifications and codes, calculation errors, mistakes in following specifications, issues with constructability, improper engineering decisions and improper composite choice). Design errors can be avoided by rigorous checks of the design prior to the commencement of construction and ensuring performance-based design taking the fatigue, possible overload, and durability into consideration. The design errors can be mainly categorized as shown in Table 3.

Table 3. Design factors causing deficiencies in FRP

Unreasonable design	Calculation or Design errors	Inadequate installation or construction details	Improper composite choice
• Inappropriate decisions taken for the application of rehabilitation and repair systems • Improper design for construction using FRP reinforcements • Lack of appropriate design specifications and codes	• Human errors in calculation • Improper application of design specifications	• Inadequate detailing for the installation of external and construction with internal FRP • Lack of constructability checks	• Improper selection of different parameters such as fiber and matrix types, fiber length and distribution, and resin content

4.4.2 Mechanical factors

The FRP-RSC elements are subjected to dynamic (impact), cyclic (fatigue), and static (creep) mechanical loading conditions along with shrinkage and service loads. These mechanical factors could potentially deteriorate the mechanical properties of the FRP system either gradually over time or instantly which has been further discussed below.

Cyclic Fatigue

Fatigue is the degradation in the mechanical properties of a material under repeated loads. The behavior of FRP composites under fatigue is different from that of metals. In metals, there are two distinct phases, damage initiation and damage propagation, of a single crack under fatigue. Whereas, in FRP composites, an accumulation of damage mechanisms in global fashion rather than in localized fashion and without the initiation phase (as in metal) controls, which includes fiber-matrix debonding, matrix cracking, delamination, and fiber fracture. The damage mechanisms in externally applied FRP composites under fatigue are matrix cracking, transverse cracking, interfacial debonding, delamination, and fiber breaking. For internal FRP reinforcement, fatigue can lead to deterioration of the bond strength of the embedded FRP bars depending on the surface treatments, materials, environment, and loading conditions.

Creep rupture

FRP composites may undergo creep rupture when micro-cracks and voids introduced during the FRP fabrication process further develop under sustained loading conditions and are exposed to moist, saline, or alkaline environments as shown in Figure 33. Creep can also lead to bond slip in internal FRP rebars through the mechanism of volume change, however with the use of higher compressive strength concrete the creep slip can be lowered.

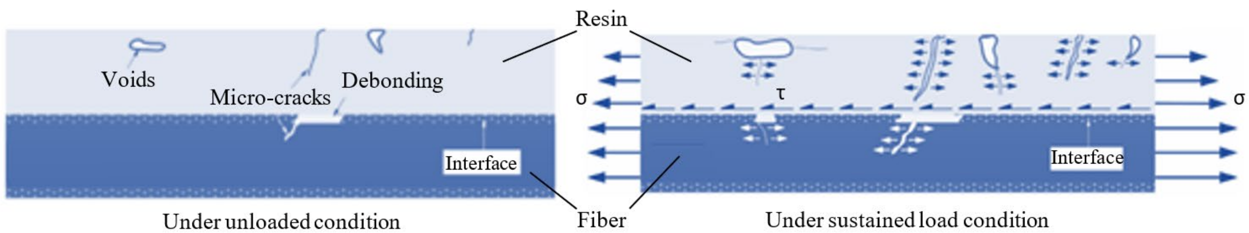


Figure 33 Deterioration under sustained load (Adapted from**:** (Chang et al. 2021)**)**

Unrestrained Shrinkage

FRP composites shrink due to decrease in volume of resin due to chemical loss as well as by thermal contraction during curing cycle. This could result into the formation of voids and cracks in the FRP composite. However, it should be noted that defects due to shrinkage in FRP composite can only occur during manufacturing processes.

Impact

Impact loads due to moving objects might cause either clearly visible surface defects or hidden subsurface defects in FRP-RSC elements.

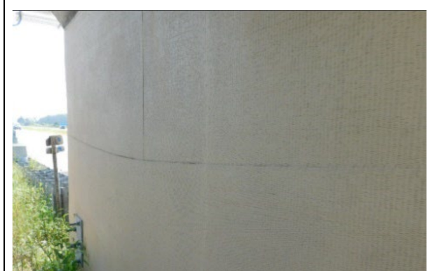
4.4.3 Environmental factors

The extended exposure of FRP composites to different environmental factors such as water, salt, alkali, ultraviolet light, elevated temperatures, and freeze-thaw cycles could potentially degrade the components of FRP composites and the interfaces in both the external and internal application of FRP. Alkaline exposure is identified as the most damaging condition, with CFRP displaying superior performance in aggressive environments, while GFRP exhibits resilience across various conditions. The significance of the glass transition temperature (Tg) is crucial for both applications (i.e., internal and external), FRP composites could lose their bond with concrete when subjected to service temperatures approaching their Tg. Guidelines highlight the importance that FRP composites should not be utilized in environments where the service temperature exceeds 27°F below their Tg.

4.4.4 Fabrication & workmanship

The sources of deficiencies associated with the fabrication and workmanship errors in the FRP composites can be classified as manufacturing errors (anywhere off-site), termed as installation/casting errors (on-site), or during transportation, storage, and handling (Table 4).

Table 4. Fabrication & workmanship factors introducing defects in FRP-RSC elements
(Malla et al. 2023)

Manufacturing errors	Transportation, storage, and handling errors	Installation errors
 FRP composites are manufactured by a variety of methods, and the defects can be introduced at any stage of manufacturing anywhere within the matrix, fiber, and interface of the composite. They are more susceptible to variations in material and geometric properties due to their complicated manufacturing processes, as can be seen in the figure above which shows an example of incorrectly bent bars by manufacturer.	 FRP composites may bend, break, and get coated with dirt, oil, or other materials during transportation as shown in figure above (GFRP bars broken due to coiling on a reel with unacceptably small diameter). Similarly, improper lifting, dropping, and dragging during handling introduce deficiencies in them. Care should be taken for their storage as prolonged exposure to UV rays and temperatures above 120 °F deteriorate their mechanical properties.	 Workmanship problems, faulty equipment used for their application, unfavorable temperature or moisture conditions, inconsistent surface preparation, improper mixing or quantity of resins, uneven distribution of resins, inadequate curing of resins, inconsistent layering and sagging of FRP plies (as shown in figure above), and many other deviations from the suggested method of their installation could all result in errors during the installation of external FRP.

4.4.5 Etiology of Deficiencies in FRP-RSC Elements

The deficiencies etiology (cause and effect) shown in Table 5 establishes a rational relationship between the observed or expected defects in FRP-RSC elements and their causes. This table can be used to trace back the cause of a defect observed during the inspection of the FRP-RSC elements. Further, deficiency etiology dedicated to FRP-RSC elements aids in effective and accurate detection of deficiencies and analyzing their impact on serviceability and structural performance.

Table 5. Etiology of deficiencies

Source of Deficiencies / Deficiencies	Design Factors	Mechanical Factors	Environmental Factors	Fabrication Errors	Workmanship
A.1 Blisters			X	X	X
A.2 Wrinkling				X	X
A.3 Scratches		X			X
A.4 Discoloration		X	X		
A.5 Fiber exposure		X	X		X
A.6 Voids at fiber-matrix interface			X	X	X
A.7 Debonding at fiber-matrix interface	X		X	X	X
A.8 Delamination between composite layers	X	X	X	X	X
A.9 Cracks in FRP	X	X			X
A.10 Impact damage		X			
B.1/ D.1 Debonding between FRP and concrete		X	X		X
B.2/ C.1/ D.2 Voids between FRP and concrete		X	X		X
E.1 Cracks in Concrete Substrate	X	X			
E.2 Voids in concrete			X		X
E.3 Concrete Delamination	X	X			
F.1 Cover separation	X	X			
F.2 Corrosion in steel reinforcement			X		
G.1 Loss of cross-sectional property			X		
H.1 Debonding of internal FRP reinforcements		X	X		
H.2 Slippage		X	X		
I.1 Cracks in FRP reinforced concrete	X	X			

SECTION 5 INSPECTION

Deficiencies in FRP-RSC elements negatively affect the structural integrity and serviceability of FRP-RSC elements. NDT tools capable of detecting these defects for both the embedded FRP rebar and the externally bonded FRP composite applications. NDT methods are needed to ensure construction quality and continued structural integrity. NDT is vital because the failure of structures reinforced with FRP rebars is not as ductile as conventional constructions, and concrete structures strengthened with externally bonded FRP composites are covered and cannot be inspected as readily. NDT methods that can inspect beyond the FRP wraps or laminates to examine the internal integrity of the element should be evaluated.

5.1 INSPECTION TECHNIQUES

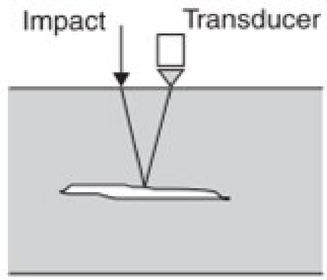
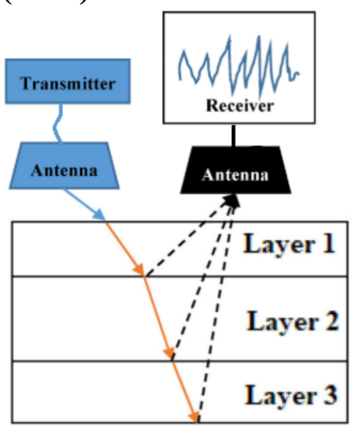
This section reviews non-destructive testing techniques that could potentially be applicable to FRP inspection through a literature survey of past studies, applications, and research projects. These methods were selected from a pool of 28 NDT methods available for damage detection in structural elements. For each NDT technique, its theoretical principles and its applicability to FRP-RSC inspection are discussed in detail in the accompanying report. Table 6 provides a brief overview of selected methods, including their descriptions, applications, advantages, and disadvantages. This information serves as the foundation for choosing the most suitable methods.

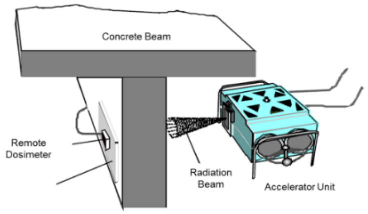
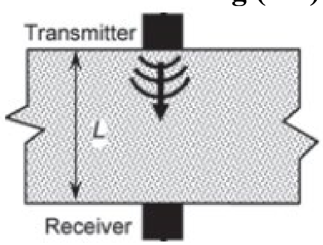
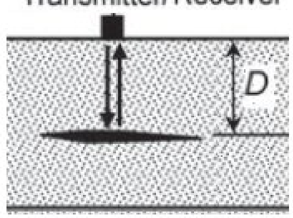
5.2 SELECTION OF APPLICABLE NDT METHODS

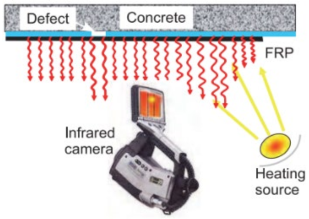
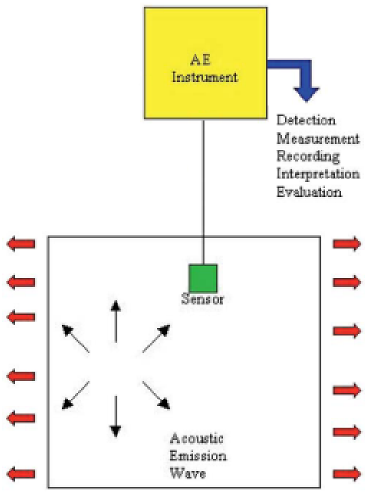
The following flowchart (Figure 34) is presented to show NDT methods applicable for inspection of concrete elements reinforced or strengthened with FRP. The flowchart also suggests the order of priority of various NDT methods, type of deficiencies, and type of applications.

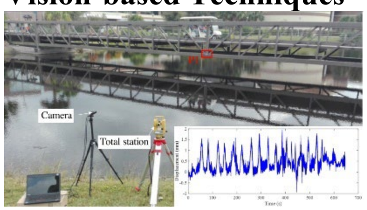
Table 6. NDT methods applicable for FRP inspection (Dolati et al. 2023)

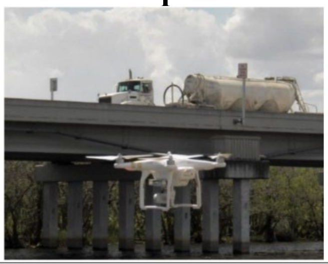
Method	Description	Advantages	Disadvantages
Visual Inspection (VT) 	• The most common, versatile, and simplistic NDT method that can be used for inspecting FRP- RSC elements, • Defects such as cracks, delamination, fractures, blisters, debonding, moisture accumulation, fiber misalignment, discoloration or any other surface defects can be detected by visual inspections.	• Checks obvious and outstanding anomalies, • Fast, simple and cost effective, • Real-time inspection and can be interpreted instantly, • Sets the baseline for other NDT methods, • Based on the findings of visual inspection, decisions can be made on necessity of further inspection with more sophisticated NDT methods, • Can be performed before any other NDT as a supplementary method.	• Detects only surface defects, • Subjective and observations may vary depending on visual perceptions of individuals.
Tap Testing (TT) 	• The local stiffness of a laminated material within a defective area differs from that in sound areas which causes a variation in the frequency of excitation upon impact, • In this method, defects (i.e., voids, debonding, delamination) are determined by tapping the test object with a coin or a hammer, and then listening for a change in (frequency of) the sound produced.	• Faster inspection, • Can inspect large areas, • Low cost, • Easy to use method with some training, • Real time and provides immediate results.	• Subjective as it relies on the human factors, • Results vary due to the inconsistencies in the force, angle and devices used, • Ambient noise and geometric changes may lead to erroneous interpretation, • Does not provide the depth and width of the defects.

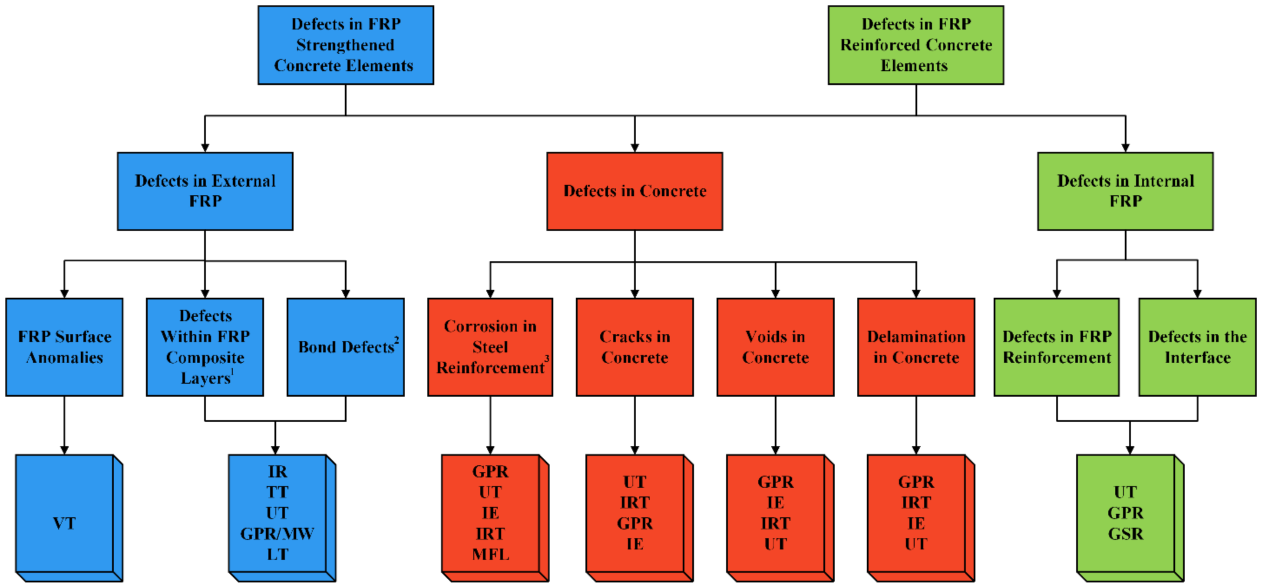
Method	Description	Advantages	Disadvantages
Impact Echo (IE) 	• Uses stress waves or mechanical waves generated by an impact (by a small hammer or a steel sphere) that propagate through the member and reflect back due to variation in acoustic impedances caused by the presence of discontinuities, • The reflected waves recorded by a displacement transducer are analyzed to give information about the extent and location of the subsurface defects.	• Has deep penetrating capability into concrete, • Promising for evaluation of cracks, voids, delamination, and discontinuities in concrete, • Unlike ultrasonic methods, impact echo utilizes lower frequency which allows the impact echo to overcome high-signal attenuation, • Needs only one surface to be accessible for testing.	• Current instrument limited to testing members up to 40 in. (1 m) thick, • Operate by experienced personnel, • Smaller cracks and discontinuities cannot be detected easily.
Ground-Penetrating Radar (GPR) 	• Operates by transmitting electromagnetic waves (radio waves) through the test material and by receiving the waves that are reflected off the discontinuities within the material, • These discontinuities could be any interface between different materials (such as concrete-rebar interface) or subsurface defects like voids, cracks, debonding, and delamination (concrete-air interface or concrete-water interface).	• Penetrates beyond concrete-air interfaces which allows inspection of features below the interface, • Detects defects at a greater depth than some other NDT techniques such as infrared thermography, • Air-coupled GPR allow rapid inspection.	• Relatively more expensive than other NDT methods, • Not suitable for detecting air-filled defects.

Method	Description	Advantages	Disadvantages
Radiographic Testing (RT) 	• Operates by recording the intensity of high-energy electromagnetic radiation, such as X-rays and Gamma rays, on a photographic film after passing them through the test material, • The differences in the intensity of the radiation that can be seen as shadows or bright spots in the photographic film give information about the internal features of the member such as voids or delamination.	• Can clearly detect the defects like delamination in the FRP as there would be variations in the absorption of the radiation between the sound and defective regions, • Defects that cause significant density variations, such as excess density of fiber or matrix, resin variations, impact damage, delamination, debonding, foreign contamination, cracks, and voids, can be easily detected, • Can also detect non-uniform fiber distribution, broken fiber, poor fiber weaving, and misorientation in fibers, such as fiber wrinkles.	• If the orientation of the delamination is perpendicular to the radiations, these defects will not be detected in a 2D scan, • More expensive than other NDT methods, • Safety issues from high intensity radiations.
Ultrasonic Testing (UT)  	• Works based on the principle that when the ultrasonic waves come across an interface between two materials with different acoustic impedances, a portion of the incident wave will be reflected back, • Has been very successful in locating defects within concrete and composites as there is almost a total reflection at the interface present due to defects.	• Fast, easy to use in fields and has good resolution, • Can penetrate well into the materials and detect subsurface flaws, • Detects wide range of defects such as debonding, resin variations, broken fibers, impact damage, moisture, cracks, voids, and subsurface defects.	• Highly trained individual to conduct the test and interpret the data, • Applicable to limited thickness of members.

Method	Description	Advantages	Disadvantages
Infrared Thermography (IR) 	• Works based on the principle that the thermal properties (thermal conductivity) of the anomalies present within the element are different than that of the surrounding sound part, • It can detect subsurface anomalies to some extent by measuring the surface temperature.	• Detects subsurface defects globally over larger surface areas, • Fast and inexpensive, • Inspections and data interpretation can be performed in real time.	• Not reliable enough in detecting water-filled defects, • Cannot effectively detect defects present deep within the concrete, • Needs proper environmental/ambient conditions.
Acoustic Emission (AE) 	• Operates by detecting the elastic waves generated by sudden redistribution of stress produced due to moving dislocations, onset/growth/propagation of cracks, fiber breaks, debonding, and plastic deformations.	• Allows fast and global inspections, • Can be performed without interruption to the service of the structure, • Detects defects due to fatigue loading such as fatigue cracks, fiber fractures, matrix micro-cracks, fiber-matrix debonding, and delamination, • Effective in locating the origin/location of discontinuities, • Detects the growth rate of a defect.	• Difficulty in differentiating deficiency source, • Needs high level of skill in correlating the AE data to respective deficiency sources, • Noisy environment may lead to false signals, • Defects might go undetected if the loading is not sufficient, • Cannot give information on the type and size of defects, • Not capable of detecting deficiencies occurred before sensor installation.

Method	Description	Advantages	Disadvantages
Global Structural Response Testing (GSR) • **Modal Testing** • **Load Testing** 	• The principle behind modal testing is to evaluate the condition of a structure by monitoring the changes in its dynamic response/ behavior (typically, modal frequencies and modal shapes), • The principle behind load testing is to evaluate the condition of a structure by monitoring the changes in its static response such as increase in deflection of a structure under externally applied load.	• Effective for assessing the efficacy of the FRP rehabilitations, • Applicable for long term performance of structures.	• The local defects may not be significant enough to contribute to global response, • Lacks sensitivity to finer localized defects and cannot give information on their size, location, and magnitude.
Complementary to NDT Method: **Vision-based Techniques** 	• Uses photographs and videos as the primary means of analysis and assessment, • At the local level, it can detect surface defects such as cracks and delamination, as well as internal structural issues through the use of visual and infrared imaging, • At the global level, it can be used to analyze the overall structural health by tracking and analyzing parameters such as displacement, vibration, and modal behavior.	• Non-contact measurements, • Remote data collection, • Low cost and less time consuming, • Less labor intensive, • Minimum interference to traffic.	• Precision can be affected by vibrations and movement of camera, • The field of view could be distorted due to environmental factors which can give erroneous observations.

Method	Description	Advantages	Disadvantages
Complimentary to NDT Method: **Robotic Inspection** 	• Involves the use of NDT techniques integrated with robots, • The robots used for NDT application can be divided into aerial robots, ground robots and underwater robots.	• Less time consuming, • Automated robotic inspections are quite efficient, • Can reach places where humans cannot, • Reduces the risk of accidents involving humans.	• Environmental factors such as improper lighting, ambient noise, high wind speed, weather conditions, low visibility, etc. affect vision-based robotic inspection, • Restrictive regulations in flying UAVs, • Difficulty in maneuvering robots in congested space.



Notes:

1. Defects within FRP composite layers include blisters, wrinkling, scratches, discoloration, fiber exposure, voids at the fiber-matrix interface, fiber-matrix debonding, delamination between composite layers, cracks, and impact damage
2. Bond defects include debonding and voids between FRP and concrete
3. Corrosion in steel reinforcement is to be considered only when it is applicable

Acronyms:

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

Figure 34 Order of priority for NDT methods suitable for each type of defect (Source: Authors)

5.3 INSPECTION TYPE

The type of inspection to be applied depends upon the condition of the bridge and it is important to understand the inspection types for adequate inspection of any bridge. The types of inspection as defined by NBIS 23 CFR § 650.305 are briefly introduced in this section.

5.3.1 Initial Inspection

The first inspection of a new, replaced, or rehabilitated bridge. This inspection serves to record bridge inventory data, establish baseline conditions, and establish the intervals for other inspection types.

5.3.2 Routine Inspection

Regularly scheduled comprehensive inspection consisting of observations and measurements needed to determine the physical and functional condition of the bridge and identify changes from previously recorded conditions. The routine inspection interval should follow NBIS.

5.3.3 Damage Inspection

An unscheduled inspection to assess structural damage resulting from environmental factors or human actions.

5.3.4 In-Depth Inspection

A close-up, detailed inspection of one or more bridge members located above or below water, using visual or nondestructive evaluation techniques to identify any deficiencies not readily detectable using routine inspection procedures. Hands-on inspection may be necessary at some locations.

5.3.5 Special Inspection

An inspection scheduled at the discretion of the bridge owner, used to monitor a particular known or suspected deficiency, or to monitor special details or unusual characteristics of a bridge that does not necessarily have defects.

5.3.6 Other Inspection

Hands-on inspection: Inspection within arm's length of the member. It uses visual techniques that may be supplemented by nondestructive evaluation techniques.

Underwater inspection: Inspection of the underwater portion of a bridge substructure and the surrounding channel, which cannot be inspected visually at low water or by wading or probing, and generally requiring diving or other appropriate techniques.

5.4 INSPECTOR QUALIFICATIONS, SITE SAFETY, AND OTHER CONSIDERATIONS

To ensure proper inspection of structures, inspection team leaders must meet the qualifications outlined in the Code of Federal Regulations (23 CFR 650.309), the most recent edition of the AASHTO Manual for Bridge Evaluation, and as specified by the state DOTs. Furthermore, inspectors should have experience and be familiar with FRP material and able to recognize the need for advanced inspection methods. The inspectors should be able to analyze and interpret the resulting data. Nondestructive testing (NDT) engineers employed by the highway organizations or consulting firms may be conduct some of the highly specialized inspections.

To ensure safety and compliance during inspections, the team leader should plan and oversee traffic control, access, equipment, and other site-related matters. This should be performed in accordance with regulations and guidelines, including those of the U.S. Department of Labor's Occupational Safety and Health Administration, the Manual of Uniform Traffic Control Devices, and the AASHTO Manual for Bridge Evaluation. Additionally, state or local regulatory authorities may have their own specifications, which should be observed when addressing issues associated with fieldwork.

5.5 INSPECTION PROCEDURE

Section 4 classified deficiencies in two main categories of FRP application. Accordingly, the inspection of FRP-RSC elements is discussed separately for the same two categories, FRP strengthened bridge elements and FRP reinforced bridge elements.

5.5.1 FRP Strengthened Bridge Elements (External Application)

The inspection of FRP strengthened bridge elements can be conducted for three different categories of deficiencies. The first category (Section 5.5.1.1) includes inspection for the deficiencies that are readily visible on the surface and fall under the FRP composite defect mentioned in Section 4.1.1. The second category (Section 5.5.1.2) includes the inspection of deficiencies that occur in the FRP composite itself and at the bond layer between the FRP and the concrete. Finally, the third category (Section 5.5.1.3) involves inspection for deficiencies in the concrete substrate. Figure 35 shows a summary of deficiencies expected in FRP strengthened concrete bridge elements during inspection.

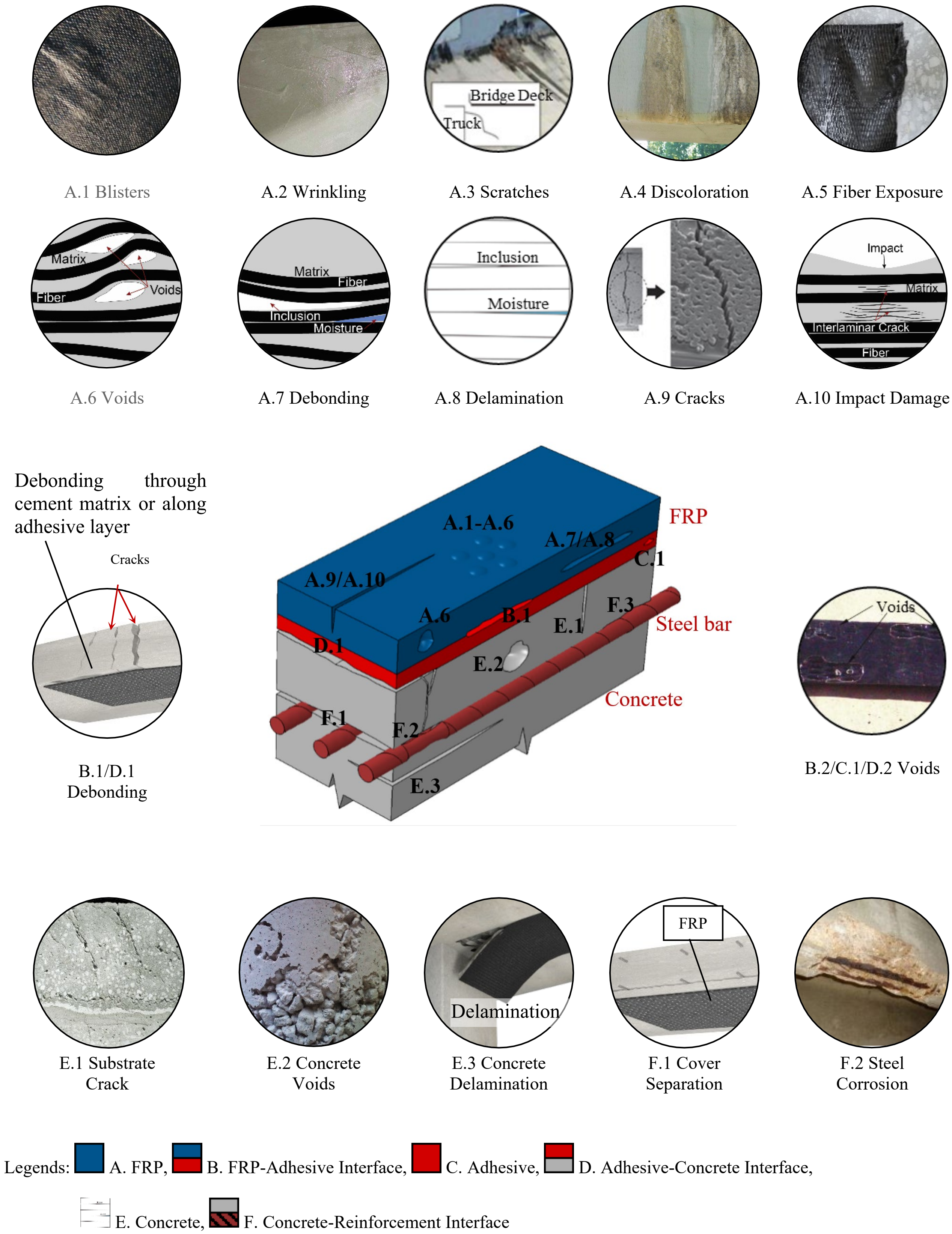


Figure 35 Deficiencies in external FRP application (Source: Authors)

5.5.1.1 Inspection for Surface Anomalies and Defects

The externally applied FRP system should be thoroughly investigated visually. Although the focus of the visual inspection is the externally bonded FRP, the overall condition of the bridge should also be visually assessed. As a minimum, the following should be checked during the inspection:

- Look for signs of surface anomalies such as blisters, fiber exposure, scratches and cracks on the surface of the externally applied FRP (Figure 36, Figure 37 and Figure 38).

- Look for signs of moisture, water seepage, efflorescence, and water stains (Figure 39 and Figure 40) usually appearing near joints or lower areas underneath the structures.

- Check for regions of discoloration, usually occurring at areas exposed to UV rays but could be from other exposures, even from impact (Figure 41).

- The surface anomalies observed in externally applied FRP could be an indication of defects within the FRP composite or the bond defects between the FRP and concrete. Use suggested NDT methods mentioned in Section 5.2 for determining the extent of the observed deficiencies if warranted.

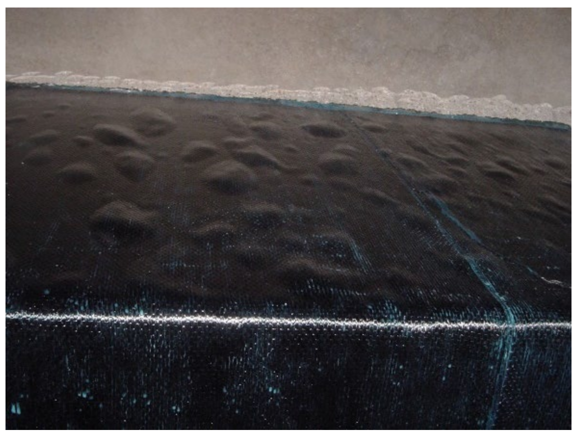


Figure 36 Blistering/Bubbles in FRP (Source: Authors)

Figure 37 Fiber exposure (Baniya et al. 2022)

Figure 38 Cracks (Source: Authors)

Figure 39 Rupture due to moisture entrapment (Source: Authors)

Figure 40 Efflorescence near joints of adjacent box beam girders (Baniya et al. 2022)

Figure 41 FRP discoloration (Pevey et al. 2021)

5.5.1.2 Inspection for defects in FRP Composite and Bond Issues

The inspection for defects in FRP composite and bond defects may be evaluated by NDT methods other than visual inspections. Tap testing should be used for bond damage detection. If warranted, IR, GPR or UT can be used in addition for quantitative assessment of the deficiencies present within FRP composite or in between FRP and the concrete substrate. The following steps should be performed as a minimum:

- Check for signs of debonding and delamination in externally applied FRP. Look for evidence of loosely bonded FRP that could be effortlessly peeled from the concrete substrate. Attempt to determine whether the defect is delamination within the layers of FRP composite or debonding of the FRP from the concrete substrate. Use tap testing to identify location of debonding/delamination in addition to visual inspection. Figure 42 and Figure 43 show examples of debonding and end peeling.

- Look for potential signs of voids. The voids could be either visible at the surface as shown in Figure 44 or show some indication of their presence as shown in Figure 45. The areas suspected of having void (Figure 45) should 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 Section 5.2.

Figure 42 Debonding (Baniya et al. 2022; Pevey et al. 2021)

Figure 43 End peeling (Baniya et al. 2022)

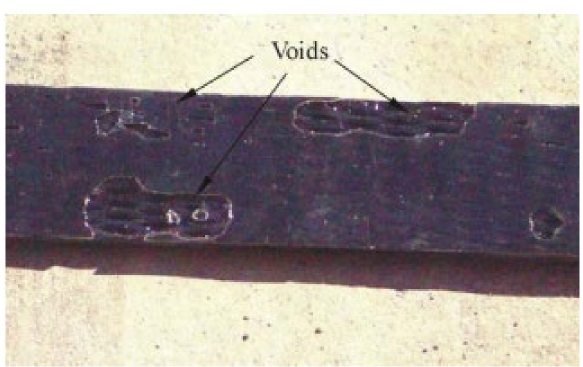


Figure 44 Void (Karbhari et al. 2005)

Figure 45 Potential void (Baniya et al. 2022)

5.5.1.3 Inspection for defects in Concrete Substrate

The inspection of concrete hidden beneath the externally applied FRP composite is a challenging task. However, this can be achieved through inspection of evidence that indicates the presence of defects in the underlying concrete. The inspection of concrete substrate, at a minimum, should include the following activities:

- Look for signs of FRP tearing due to spalling of the concrete substrate as shown in Figure 46.

- Look for the signs of abnormalities, mostly deviations from the surrounding sound external FRP regions, that would indicate presence of defect underneath the FRP. Figure 47 shows bulging of CFRP layer along the soffit of a girder indicating the presence of a longitudinal crack at the substrate.

- Check for signs of rust stains as shown in Figure 48. Rust stains over externally applied FRP indicates the corrosion of steel reinforcement embedded in the FRP strengthened concrete elements.

- NDT devices that can penetrate through the external FRP composite layer should be used at suspected areas for further investigation.

Figure 46 Spalling of substrate concrete causing tearing of externally applied CFRP
(Baniya et al. 2022)

Figure 47 Bulged CFRP layer indicating the presence of a longitudinal crack beneath
(Baniya et al. 2022)

Figure 48 Rust stains indicating corrosion of steel reinforcement in concrete substrate
(Jung, Jeong, and Lee 2022)

5.5.2 FRP Reinforced Concrete Bridge Elements (Internal Application)

In general, the inspection of RC regardless of the type of reinforcement has been covered widely by the bridge inspection and evaluation manuals and guidelines. The inspection of FRP internal application differs from the conventional steel-RC, as many of the serviceability issues related to conventional RC such as cracking, permeability, carbonation, chloride content, and concrete cover may not pose the same concern for FRP-reinforced elements. On the other hand, FRP materials may be prone to such problems as creep rupture and alkaline exposure that are of no concern for steel rebars. The following offers guidance for inspection of FRP-RC elements beyond or complementary to the procedure used for conventional steel-RC elements. Inspection of FRP-PC (FRP prestressed concrete) has not been covered in this framework.

Because internal FRP is hidden from eyes, the inspection of FRP reinforced bridge elements involves looking for the cause (sources mentioned in Section 4.4) and the respective evidence or indications of the deficiencies in the element. Since the deficiencies in FRP reinforced concrete elements are not as obvious as FRP strengthened concrete elements, their presence can be indirectly inferred from the signs of abnormalities (such as water seepage/stains, cracks, spalling, deflections, etc.), especially if occurring together with the potential causes/sources of deficiencies (such as excessive water/alkaline exposure, elevated temperature, extreme loading conditions, etc.) as shown in Figure 49. For instance, with reference to Figure 49, instead of directly detecting the debonding of FRP bar (shown in the center image), the inspector can look for relevant evidence such as excessive deflection (shown under evidence column), the unusual causal factors such as extreme loading conditions (shown under causes column), or both. The potential deficiencies in FRP before completion of the bridge that might have occurred during manufacturing/installation, transportation, storage, and handling of FRP material is not considered or covered in this framework unless they become evident due to presence of other in-service deficiencies. Further, when and if a relationship between the cause/evidence and potential deficiencies are established, NDT inspection on suspected areas can be conducted using the methods suggested in Section 5.2 if warranted.

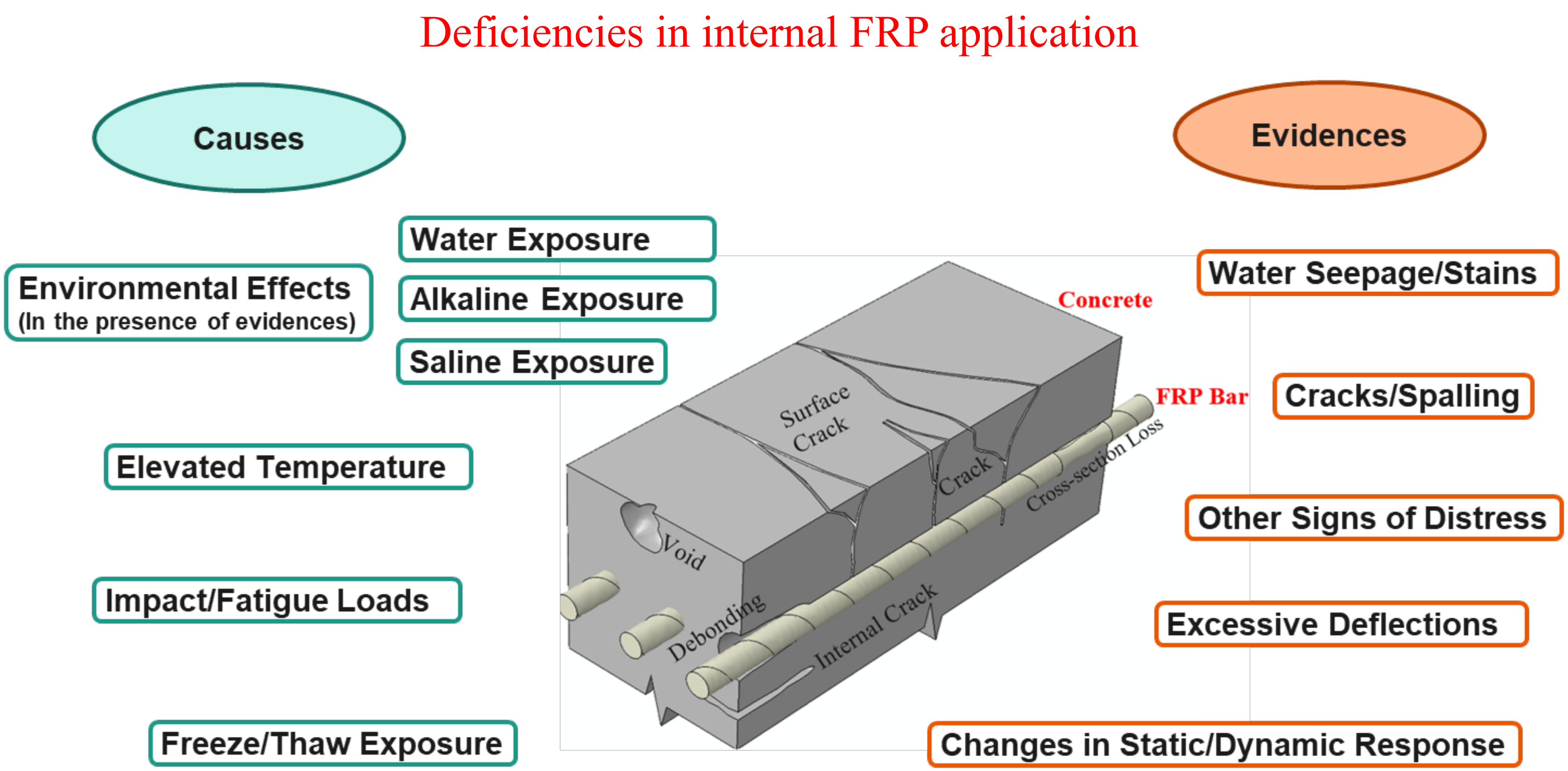


Figure 49 Causes and evidence for potential deficiencies in internal FRP application (Source: Authors)

5.5.2.1 Inspection of Concrete

For the inspection of concrete, as stated above, general purpose bridge inspection manuals and references listed in Section 1.5 should be followed. Also, refer to Section 5.2 of this framework for more details on the selection of inspection methods for concrete inspection.

5.5.2.2 Inspection of Internal FRP

As mentioned earlier, the inspection of internal FRP can be carried out by attention to the causes and evidence. It should be noted that in most cases, the presence of detrimental environmental effects would not necessarily indicate a potential for deficiency in FRP if evidence is not also present. On the other hand, in some cases, the presence of evidence alone could be suspected as internal FRP deterioration such as the case of cracks and excessive deflections. Some of the evidence to look out for with their respective causes are described as follows:

- Look for signs of water seepage into the element, as shown in Figure 50, as it could mean that the water has penetrated to the level of the internal FRP reinforcement creating potential for deterioration in their mechanical properties. If supported by the presence of stains, this could indicate saline exposure. However, moisture exposure is not a cause of deterioration.

- Check for cracks in the FRP reinforced concrete elements, especially on bridge decks. Cracks are the most common types of damage occurring in the FRP reinforced concrete elements due to lower modulus of elasticity of the FRP bars. The cracks visible on the surface of the bridge decks reinforced with FRP rebars are shown in Figure 51.

- Check for any signs of distress such as fire damage with excessive spalling or burn marks as shown in Figure 52.

- Deflection measurement as shown in Figure 53 under live load or dead load alone can be carried out to assess the overall performance of the FRP reinforced bridges. FRP reinforced concrete elements exhibit higher deflections than steel-reinforced concrete elements of same size, shape, and reinforcement ratio. Having deflections higher than the design deflection limits specified by AASHTO can be construed as a potential presence of damage in the internal FRP.

- Deficiencies in FRP reinforced concrete elements can also be detected by using damage detection methods based on variations of bridge dynamic response (natural frequency and mode shapes) as shown in Figure 54.

- The presence of damage and its location, type, and severity in internal application of FRP can be further verified by using NDT methods suggested in Section 5.2.

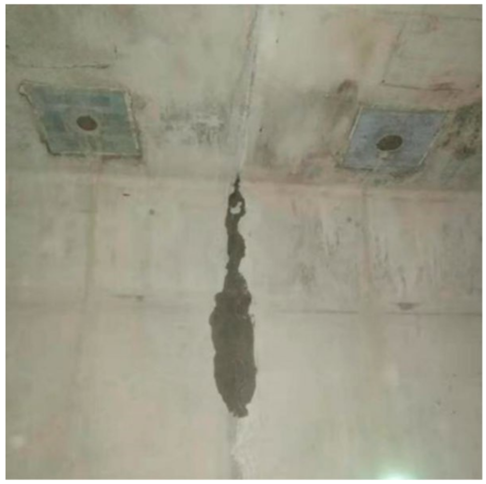


Figure 50 Water seepage (Wang and Fan 2020)

A. Longitudinal cracks B. Crack width of 1/16 in C. Extensive cracking

Figure 51 Cracks in FRP reinforced bridge decks (Valentine 2015)

Figure 52 Fire damage (Graybeal 2007)

Figure 53 Deflection measurement (El-Salakawy, Kassem, and Benmokrane 2002)

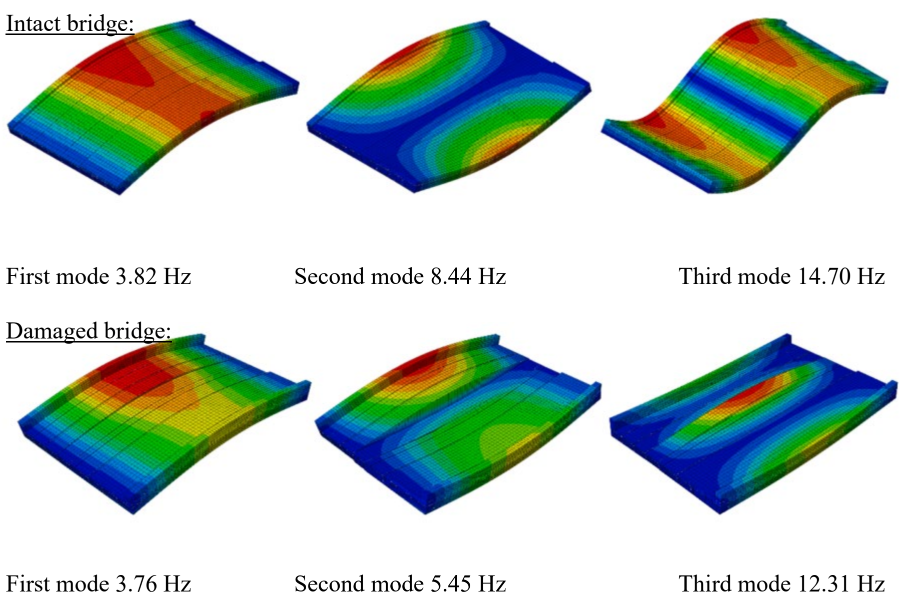


Figure 54 Changes in dynamic response (modal shapes) (Abedin et al. 2022)

SECTION 6 RECORDKEEPING

6.1 PROCEDURE FOR RECORDING OBSERVATIONS

To ensure that any deficiency of the FRP-RSC elements is well-documented, it is essential to record observations during the inspection that clearly indicate the location, extent, type, and severity of the deficiency. A consistent and standardized method of recording observations provides a means to compare observations using uniform evaluation criteria, which facilitates the assessment of the severity of observed conditions and determination of appropriate action. Sufficient details and descriptions should be included in the notes to be meaningful and useful for evaluating and rating of the FRP-RSC elements. As a minimum, the detailed description of observations should include specific information such as:

- **Location of observed condition**: Reference the location of the FRP-RSC element from an easily identifiable point when documenting observed condition. Section 2 of the AASHTO Manual for Bridge Element Inspection (AASHTO 2019) gives the inspector a master location matrix of all the elements and identification numbers for quick reference. Specify the location of the deficiency within the element to provide clear and precise references for the location. Consider including a sketch to make it easier to identify the location.
- **Extent of the observed deficiency or condition**: Record the width, length, and depth of the observed condition, include sketches of the condition to supplement the written description.
- **Type of deficiency or observed condition:** This can include observations from several inspection methods. Visual inspection could give an indication of discoloration, cracks, delamination, and wrinkling. In acoustic or tap-test inspections, the types of deficiency could include debonding, delamination, and voids between FRP wraps and underlying concrete.
    - **Severity of observed condition or deficiency:** While the severity level is subjective, it should be determined using a consistent scale. The scale used for rating the severity of a condition should be uniform across all bridge components.
    - **Potential reasons for the identified condition or deficiency.** If feasible, make a note of the presence or absence of contributing factors. In case of cracks or other deficiencies, observe if these cracks or defects are active, meaning they are affected by loading or environmental conditions.
- **Photographs, audio recordings, videos, or other documentary evidence of the observed condition at the time of inspection**. The documentary evidence should be indexed with appropriate description and should be cross-referenced with the field notes.

6.2 EVALUATION OF HISTORIC DATA

Maintaining a record of historical data is critical to accurately identify trends in the condition of a bridge over time. This data can provide valuable information on bridge maintenance needs, help predict future problems, and guide decision-making on repair and component replacement. Inspectors should thoroughly examine previous inspection findings related to the following:

- Inspectors review all available quality assurance and quality control data for the materials used for the construction of the reinforced concrete element. If the element has undergone prior strengthening, inspectors should also examine any available information concerning the FRP system used, if applicable.
- Recorded observations taken during and immediately after construction.
- Information on any incidents or circumstances that may have caused deficiency or impacted the condition of the bridge, including vehicular impact, fire damage, or chemical damage.
- Progression of deficiency or deterioration (if any) or the strengthening/repair/retrofit system used to address the incident/circumstance.
- Record whether the circumstances causing the previous deterioration are still present.

Review these factors in all preceding inspection reports, and inspect the same areas identified in previous reports during the most recent inspection to monitor the development of these conditions over time. Analyzing the data from earlier reports against the current observations will enable the inspector to assess the gravity of the condition, the likely progression of deficiency, the condition's probable influence on the RC element, and the urgency of remedying any harmful conditions.

6.3 STANDARD CHECKLISTS

6.3.1 Pre-Inspection Checklist

- All necessary personal safety equipment;
- Flashlight;
- Small mallet or hammer;
- Feeler gages;
- Tap tester;
- Camera;
- Notepad, pencils, etc.;
- Printed forms;
- Detailed drawings of bridge and FRP-RSC member;
- Any available specifications about the materials used for the construction and/or strengthening of the FRP-RSC element;
- Other NDT devices as per the inspection scope;
- Site and operation safety analysis;
- MOT plans and coordination;
- Access and rigging plan and equipment.

6.3.2 FRP-RSC deficiency types checklist

- The checklist of evidence/cause for FRP in internal application (FRP-RC) is as follows:
    i. water seepage/stains
    ii. presence of environmental exposure (water, alkaline, saline exposure),
    iii. cracks/spalling,
    iv. excessive deflections under live load or dead load alone,
    v. other signs of distress
    vi. presence of factors such as elevated temperature, freeze/thaw exposure, etc.

- The checklist of deficiencies for FRP in external application is as follows:
    vii. voids: fiber-matrix interface (intrinsic to composites),
    viii. wrinkling,
    ix. blistering,
    x. fiber-matrix debonding and delamination between composite layers,
    xi. fiber exposure,
    xii. scratches,
    xiii. cracks,
    xiv. discoloration,
    xv. impact damage,
    xvi. voids/debonding between FRP and concrete,
    xvii. delamination/cover separation,
    xviii. cracks in concrete,
    xix. voids in concrete,
    xx. corrosion in steel reinforcement of concrete substrate

6.3.3 Inspection and Test Methods Checklist

The inspection and test methods are as follows:

Methods that normally performed within routine inspection:

- Visual Inspection (VT)
- Tap Testing (TT)

Methods that normally performed as special inspection warranted by routine inspection:

- Infrared Thermography Testing (IR)
- Ground Penetrating Radar (GPR)
- Ultrasonic Testing (UT)
- Impact Echo Testing (IE)
- Microwave Testing (MW)
- Acoustic Emission Testing (AE)
- Laser Testing Method (LT)
- Radiographic Testing (RT)

6.4 INSPECTION FORMS

Tables 7 through 10 contain inspection summary forms that serve as a useful tool for organizing the data gathered by inspectors during the inspection of FRP-RSC elements. These forms are designed to help the inspector categorize and rate the observed conditions, with the aid of field notes, sketches, photographs, and other relevant documentation. It is important for the inspector to utilize these forms effectively to ensure an accurate and comprehensive assessment of the bridge's condition. It should be noted that these tables are shown as an example and are subject to modification as needed.

Table 7. Bridge Inspection Program Information

Bridge ID/Number:		**Inspection Date: / /**	
Bridge Name:		**Inspection Type:**	
Bridge Location:		**Year Built:**	
FRP Application (External or Internal):		**Last Inspection: / /**	
Feature Carried:			
Feature Under:			
Inspection Agency:			
Inspection Team (Circle Team Leader):			
Bridge Details			
i. Total Length			
ii. Overall Str. Width			
iii. Structure type (S=simple span, C=continuous, etc.)			
iv. Number of spans and span lengths			
Element Details			
i. Length			
ii. Width			
iii. Depth			
iv. Reinforcement detail (if available)			
v. Element type (beam, column, deck, etc.)			
vi. Element ID			
FRP Details			
i. Dimension (length, width-dia.)			
ii. Fiber type (G/C/B/A-FRP)			
iii. FRP Location			
Manufacturing Process			
i. Wet layup			
ii. Precured laminates			
iii. Pultrusion			
iv. Others			
Material Properties			
i. FRP modulus of elasticity			
ii. FRP tensile strength			
iii. Concrete compressive strength			
Inspection/Damage Detection Methods Used	Yes?	Detailed field note page reference	Instrument(s) used
i. Visual Inspection (VT)			
ii. Tap Testing (TT)			
iii. Impact Echo Testing (IE)			
iv. Ground Penetrating Radar (GPR)			
v. Ultrasonic Testing (UT)			
vi. Infrared Thermography Testing (IR)			
vii. Global Structure Response (GSR)			
viii. Other:			
Note: Supplementary drawing attached?			

Table 8. Element Inspection Summary Form

Bridge ID/Number:		**Inspection Date: / /**	
Bridge Name:		**Inspection Type:**	
		Inspection Technique:	
Bridge Location:		**Year Built:**	
FRP Application (External or Internal):		**Last Inspection: / /**	
Feature Carried:			
Feature Under:			
Inspection Agency:			
Inspection Team (Circle Team Leader):			
Element inspected:		**Element ID:**	
Element Detailing			
i. Width, Depth and Length			
ii. Reinforcement (if available)			
iii. Concrete compressive strength (if available)			
Deficiency Types Observed Based on Location	Yes?	Detailed field note page reference	Is the deficiency active? (causal element exists)
i. Concrete			
Delamination/Cover Separation			
Voids			
Cracks			
Others			
ii. Internal FRP Application			
Evidence pointing to misplacement or potential deficiency (If yes, describe the evidence below)			
Evidence			
Others			
iii. External FRP Application			
Voids: Fiber-Matrix Interface (Intrinsic to Composites)			
Wrinkling			
Blistering			
Fiber-Matrix Debonding & Delamination Between Layers			
Fiber Exposure			
Scratches			
Discoloration			
Impact Damage			
Voids/Debonding Between FRP and Concrete			
Corrosion in Steel Reinforcement (if any)			
Others			
Global Response			
Excessive Deflection			
Change in Static/Dynamic Response			
Others			
Supplementary NDT/other forms			

Table 9. Example of GPR Data Collection

Ground Penetrating Radar (GPR) Inspection Form							
Element ID				Inspection Date			
GPR Measuring Presets							
Filename				Device Name & Central Frequency			
Measuring Mode:							
☐ Line Scan				☐ Grid Scan			
Line Number				Grid Number			
Gain				Grid Size			
Filter		☐ On ☐ Off		Grid Resolution			
Concrete Cal				Concrete Cal			
Length				**Location of Grid Origin**			
Location of Line of Inspection				Distance from 1st Reference Edge			
Distance from Reference Edge (DE)				Distance from 2nd Reference edge			
Edge Reference No.				Edge Reference No.		1st Edge:	
						2nd Edge:	
Picture No.				Picture No.			
Interpretations							
Element		Backwall detectable? ☐ Yes ☐ No		Detected depth of backwall:		Remarks:	
Internal FRP Application	Rebar ID						
	Size (if discernible)						
	Location/Spacing						
	Detectability						
	Discontinuity						
Other Remarks							

Table 10. Example of UT Data Collection

Phased Array Ultrasonic (PAU) Inspection Form			
Element ID		Inspection Date	
PAU Measuring Presets			
File name		Device Name	
Measuring Mode:			
☐ Line Scan		☐ Area Scan	
X spacing (m)		Y spacing (m)	
Analog Gain (dB)		Analog Gain (dB)	
Time Gain Compensation (dB)		Time Gain Compensation (dB)	
Pulse Delay (ms)		Pulse Delay (ms)	
Maximum Transmission Time	μs	Maximum Transmission Time	μs
Location of Line of Inspection			
Distance from Reference Edge (DE)		Distance from Reference Edge (DE)	
Edge Reference No.		Edge Reference No.	
Picture No.		Picture No.	
Calibration			
Raw Data Offset (μs)		Raw Data Offset (μs)	
Global Pulse Velocity	m/s	Global Pulse Velocity	m/s
Image Processing			
Digital Gain (dB)		Digital Gain (dB)	
Surface Wave Cancellation	☐ On ☐ Off	Surface Wave Cancellation	☐ On ☐ Off
Interpretations			
Element	Backwall detectable? ☐ Yes ☐ No	Detected depth of backwall:	Remarks:

Internal Application	Rebar ID						
	Depth						
	Detectability						
	Discontinuity						
Other Remarks							

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