UNIVERSITY OF MICHIGAN

REPAIR AND STRENGTHENING OF REINFORCED CONCRETE BEAMS USING CFRP LAMINATES

Volume 2: Literature Review

by

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16. Abstract

Repair and strengthening techniques using adhesive bonded carbon fiber reinforced plastic or polymeric (CFRP) laminates (also called sheets, tow sheets, and thin plates) form the basis of a new technology being increasingly used for bridges and highway superstructures.

The study described in this report (Volumes 1 to 7) focused on the use of carbon fiber reinforced plastic (CFRP) laminates for repair and strengthening of reinforced concrete beams. Its primary objectives are: 1) to ascertain the applicability of CFRP adhesive bonded laminates for repair and strengthening of reinforced concrete beams; 2) to synthesize existing knowledge and develop procedures for implementation in the field; 3) to identify key parameters for successful design and implementation; and 4) to adapt this technique to the specific conditions encountered in the state of Michigan.

This report consists of 7 volumes:

Volume 1 – Summary Report
Volume 2 – Literature Review
Volume 3 – Behavior of Beams Strengthened for Bending
Volume 4 – Behavior of Beams Strengthened for Shear
Volume 5 – Behavior of Beams Under Cyclic Loading at Low Temperature
Volume 6 – Behavior of Beams Subjected to Freeze-Thaw Cycles
Volume 7 – Technical Specifications

Volume 2 (this volume) provides a review of existing literature on the repair and strengthening of reinforced concrete beams using external glued-on Fiber Reinforced Plastic (FRP) sheets, particularly Carbon Fiber Reinforced Plastic (CFRP) sheets. A special emphasis is placed at synthesizing the information so as to allow the reader to first comprehend the material, and then make rational decisions about its use. Useful sources of information and contact persons throughout the US are also gathered. First, the mechanical properties of different FRP sheets, made with different types of fibers such as Carbon, Glass, and Aramid, are compared to the properties of steel plates. A summary of the technical data of the commercial CFRP sheets is then presented. Information about the epoxy necessary to glue the CFRP sheets to the structural element is provided as obtained from different suppliers. Different application procedures of CFRP sheets glued-on to the surface of concrete beams are documented. Specific information concerning surface preparation, mixing of adhesives, application of the CFRP sheet to the structure, and additional limitations and safety precautions is presented for each procedure. The results of an extensive survey of a large number of research projects and field applications of glued-on FRP sheets for repair and strengthening of concrete structures in the US are summarized. Whenever possible, a summary of projects (research or field applications) that are deemed relevant to the current investigation, is presented. An analysis of the structural behavior of concrete beams externally strengthened by CFRP sheets is provided Issues related to durability, which is of concern to the current study, are addressed. A summary of the recommendations for the current study based on what was learned from the literature review is presented, and an extensive list of references classified by source is provided.

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PREFACE

This project titled: *"Repair and Strengthening of Reinforced Concrete Beams using CFRP Laminates"* is aimed at providing experimental verification and recommendations for implementation of a new technology, in which thin fiber reinforced plastic laminates are glued-on the surface of concrete beams in order to strengthen them.

The primary objectives of the project are:

- To ascertain the applicability of Carbon Fiber Reinforced Plastic (CFRP) glued-on plates for repair and strengthening of concrete beams;
- To synthesize existing knowledge and develop procedures for implementation in the field;
- To adapt this technique to the specific conditions encountered in the state of Michigan.

The project consists of 8 tasks over a period of two years (8 trimesters). The following tasks (accomplishments) are planned:

- A report containing a literature review and a comprehensive synthesis of the latest state of knowledge on the glued -on FRP technique (Task 1);
- Laboratory testing and verification of the selected CFRP glued-on technique according to the proposed experimental program: bending (Task 2), shear (Task 3), freeze-thaw (Task 4), temperature and high cyclic amplitude load (Task 5);
- An interim and final report summarizing the experimental results (Task 6). The interim report will cover the bending and freeze-thaw tests;
- A summary of field specifications and "how to" details for implementation in field applications;
- Guidelines for design based on the experience developed from the experimental work (Task 7);
- Field monitoring of application of the technique to one bridge selected by MDOT (Task 8a);
- Bridge testing before and after application of the glued-on plate (Task 8b to be conducted by professor A. Nowak, U of M)

This volume summarizes the literature review as per Task 1.

ABSTRACT

This report provides a review of existing literature on the repair and strengthening of reinforced and prestressed concrete beams using external glued-on Fiber Reinforced Plastic (FRP) sheets, particularly Carbon Fiber Reinforced Plastic (CFRP) sheets. A special emphasis is placed at synthesizing the information so as to allow the reader to first comprehend the material, and then make rational decisions about its use. Useful sources of information and contact persons throughout the US are also gathered.

First , the mechanical properties of different FRP sheets, made with different types of fibers such as Carbon, Glass, and Aramid, are compared to the properties of steel plates. A summary of the technical data of the commercial CFRP sheets is then presented. Information about the epoxy necessary to glue the CFRP sheets to the structural element is provided as obtained from different suppliers.

Different application procedures of CFRP sheets glued-on to the surface of concrete beams are documented. Specific information concerning surface preparation, mixing of adhesives, application of the CFRP sheet to the structure, and additional limitations and safety precautions is presented for each procedure.

The results of an extensive survey of a large number of research projects and field applications of glued-on FRP sheets for repair and strengthening of concrete structures in the US are summarized. Whenever possible, a summary of projects (research or field applications) that are deemed relevant to the current investigation, is presented. An analysis of the structural behavior of concrete beams externally strengthened by CFRP sheets is provided. Flexural and shear behavior are described as well as the different modes of failure reported in the literature. Issues related to durability, which is of concern to the current study, are addressed.

A summary of the recommendations for the current study based on what was learned from the literature review is presented, and an extensive list of references classified by source is provided.

EXECUTIVE SUMMARY

This report provides a review of existing literature on the repair and strengthening of reinforced and prestressed concrete beams using external glued-on Fiber Reinforced Plastic (FRP) sheets, particularly Carbon Fiber Reinforced Plastic (CFRP) sheets. A special emphasis is placed at synthesizing the information so as to allow the reader to first comprehend the material, and then make rational decisions about its use. Useful sources of information and contact persons throughout the US are also gathered.

Based on the literature review carried out, the following conclusions were drawn:

- Substantial amount of research on and field applications of FRP composites demonstrate the feasibility of the utilization of glued-on sheets as a strengthening technique for concrete structures. A

- Among the different FRP laminates reviewed in this study, carbon FRP composites seem the most suitable (at time of this writing) for civil engineering applications. They possess excellent mechanical and durability properties.

- The best known CFRP systems currently used are produced by Tonen, Mitsubishi and Sika. Tonen and Mitsubishi products have similar characteristics. The Sika product differs in thickness and a smaller choice of adhesives. Because they are very thin and because they can be used in different layers, Tonen *Forca Tow Sheest* are a very versatile product. Tonen offers a wide choice of adhesives and primers for different conditions of applications.

- The simple application procedures developed, have made it possible to utilize CFRP sheets in field applications. However, the application of commercial FRP strengthening systems requires strict following of the specified procedures. So far, no standardized guidelines have been developed for this technique. Proper quality of strengthening can be achieved only by following the procedures recommended by the manufacturer of each system.

- The choice of the fiber strengthening system should in all cases be based on consideration of specifics of the application, such as:

    - purpose of strengthening;
    - the design of the structure or element;
    - conditions of application of FRP system (accessibility, temperature, humidity, degree of structural damage, surface preparation procedures etc.);
    - risks involved;

- stress levels likely to occur in the retrofit system;
- duration for which the repair/retrofit is being designed for.

- Durability issues should be addressed by a more intensive experimental program to ascertain the feasibility of this technique under particular environmental conditions.

- One of the key issues in successful application of CFRP composites is proper preparation of adhesive surfaces. The greater the level of damage (or contamination) of concrete cover, the more aggressive methods are necessary to remove the contaminated layer prior to application of the CFRP plate.

- A field test is recommended as the best way to corroborate findings performed in laboratory conditions.

- The high costs of the CFRP materials used in structural rehabilitation is fully compensated by the ease of application and low costs of workmanship.

- Not all issues related to this new technology have been fully explored. Further tests are necessary in order to identify the influence of different physical, mechanical and structural factors on performance of FRP laminates. In particular durability behavior of FRP composites requires further investigation. Information on fatigue performance and long term behavior is also lacking.

CHAPTER 1
INTRODUCTION

Advanced composites are likely to play a significant role in future construction applications particularly in the strengthening and rehabilitation of existing bridges. According to the Federal Highway Administration, more than 40% of highway bridges in the United States are in need of replacement or rehabilitation ("Highway" 1989). Deficiencies of the existing inventory of bridges range, on the one hand, from normal wear and environmental deterioration of structural components to increased traffic loads demands, and on the other hand, from insufficient detailing at the time of the original design to inadequate maintenance and rehabilitation measures. Therefore, rehabilitation alone will not bring theses bridges up to current standards. Strengthening must also be considered [AZ-03].

Techniques such as external post-tensioning and epoxy-bonded steel plates have been used successfully to increase the strength of girders in existing bridges and buildings. High strength composite plates are used as an extension of the steel plating method, offering the advantages of composites materials such as immunity to corrosion, a low volume to weight ratio, and unlimited delivery length (in sheet form) thus eliminating the need for joints [SOA-1].

Composite plates usually are epoxy-bonded to the tension flange of girders, increasing both their strength and stiffness. The advantages of this strengthening technique include ease of application and elimination of the special anchorages otherwise needed in the post-tensioning method [AZ-1].

Fiber Reinforced Plastic (FRP) composites are defined, in a most generic way, as a polymeric matrix that is reinforced with strong stiff fibers. In construction applications the fiber volume fraction is up to 65%, FRP products were first used to reinforced concrete structures in the mid 1950s. Today, we can find FRP bars, cables, 2-D and 3-D grids, sheet materials, plates, etc. These composites are generally formed by extruding continuous fibers (Carbon, Glass, Aramid, etc.) embedded in a resin matrix. Resins used can be thermoset (polyester, vinyl ester, etc.) or thermoplastic (nylon, polyethylene, etc.) [SOA-1].

The main types of fibers used in civil engineering applications are Carbon, Glass, and Aramid. The most common form of FRP (fiber reinforced plastic) composites used in structural applications is called a laminate. Laminates are made by stacking a number of thin layers (laminate) of fibers and matrix and consolidating them into the desired thickness. Unidirectional FRP sheets made of Carbon (CFRP), Glass (GFRP) or Aramid (AFRP) fibers bonded together with a polymer matrix (e.g. epoxy, polyester, vinyl ester) are being used as a substitute for steel plates [SOA-1].

CFRP and GFRP laminates appear at first to be the best (most economical) candidates for the external reinforcement of concrete structures. However, in view of some properties of GFRP composites such as their sensitivity to ultraviolet radiation, their poor fatigue performance, their stress-rupture sensitivity (i.e. dramatic reduction of their tensile strength over time), and their relatively low modulus of elasticity, it is strongly believed that CFRP laminates (particularly carbon/epoxy systems) offer the highest potential as a replacement of steel in typical strengthening applications. CFRP sheets combine the qualities of very high strength and high stiffness with an outstanding fatigue performance as well as light weight for easy handling. Moreover, CFRP sheets are durable under practically every type of environmental attack which may occur in or around concrete structures [XX-21] [EMPA-12].

1.1. Organization of this Report

This report provides a review of existing literature on the repair and strengthening of reinforced and prestressed concrete beams using external glued-on Fiber Reinforced Plastic (FRP) sheets, particularly Carbon Fiber Reinforced Plastic (CFRP) sheets. A particular emphasis is placed at synthesizing the information so as to allow the reader to first comprehend the material, and then make rational decisions about its use. Useful sources of information and contact persons throughout the US are also gathered.

Chapter 2 compares the mechanical properties of different types of FRP sheets, built with different types of fibers such as Carbon, Glass, Aramid, with the properties of steel plates. It also provides a summary of the technical data, as obtained from different suppliers, of the commercial CFRP sheets and of the epoxy necessary to glue the CFRP sheets to the structural element.

Chapter 3 provides information about various procedures of application of CFRP sheets glued-on to the surface of concrete beams. Specific information concerning surface preparation, mixing of adhesives, application of the CFRP sheet to the structure, and additional limitations and safety precautions is presented here.

Chapter 4 surveys first a large number of research projects and field applications of glued-on FRP sheets for repair and strengthening of concrete structures; these are being developed by universities and technical laboratories around the world. Whenever possible, a summary of projects (research or field applications) that are deemed relevant to the current investigation, is presented. Second, an analysis of the structural behavior of concrete beams externally strengthened by CFRP sheets is presented. Flexural and shear behavior are described as well as the different modes of failure reported in the literature. In a third part, different issues related to durability, which is of concern to the current study, are addressed. Finally, a number of field applications of glued-on FRP sheets are presented.

Chapter 5 summarizes the recommendations for the current study based on what was learned from the literature review.

An extensive list of references classified by source, is provided in Chapter 6.

1.2. Sources and Classification of Information on FRP Research

The process of obtaining the information on FRP materials and research projects, involved numerous contacts with different organizations. The organizations dealing with FRP can be classified as follows:

- State and federal agencies: DOTs, FHWA, US Army;
- Universities;
- Other research institutions;
- Companies and other commercial sources.

A summary of contacts has been developed for current and future reference and is included in Table 7.1 of APPENDIX A (section 7.2). For convenience the summary of research and applications is grouped according to research teams or organizations working together. An appropriate reference code is assigned to each group (e.g. [EMPA-1]).

CHAPTER 2
MATERIALS

Different types of FRP materials are used in Civil Engineering applications for concrete structures:

- Reinforcing bars
- Prestressing tendons
- Rigid plates
- Laminates (sheets)
- Grid or meshes

Laminates are relatively a new technology. Thanks to the remarkable advantages of this material it is increasingly used for different types of repair techniques.

2.1. Features of FRP Sheets in Civil Engineering

FRP sheets can be used for the following purposes:

- Serviceability improvements:
  - Decrease in deformation (primarily deflection);
  - Reduction of stresses in steel reinforcement;
  - Crack width reduction.
- Correction of design/construction defects:
  - Insufficient reinforcements;
  - Insufficient structural depth.
- Upgrade of damaged structural parts:
  - Aging of construction materials;
  - Steel reinforcement corrosion;
  - Vehicle impact;
  - Fire impact.
- Change of loading conditions:
  - Increase of traffic volumes on bridges;
  - Increase of live loads in warehouse buildings;
  - Installation of heavy machinery in industrial buildings;
  - Vibrating structures.
- Structural modifications:
  - Removal of walls or columns;
  - Removal of slabs sections for openings.
- Seismic upgrade.
- Change in use of structure.

2.1.1. CFRP Sheets

Carbon Fiber Reinforced Plastic laminates are composite materials built from combination of carbon fibers and epoxy resin matrix. The composite possesses very high strength and elastic modulus in the fiber direction. Its fatigue properties are also outstanding. All the fibers in the laminate form unidirectional structure. The transversal strength of the composite is low. This drawback is not relevant for many strengthening applications.
In general CFRP can be classified according to:

- High-strength fibers with tensile strength up to 7000 MPa.
- High-modulus fibers with E-modulus up to 600 GPa.

The use of a particular type of CFRP depends on the purpose of application. Consideration has to be given as to whether the necessary repair measures relate to stability, fatigue safety or fitness for use. The engineer has to consider the state of stresses in the strengthened zone - compressive, tensile or shear. Accordingly, the proper type of CFRP system has to be selected and applied in the proper direction or in multiple directions.

The unidirectional FRP materials are produced by a number of companies. Every one of these producers offers Carbon Fiber sheets in a variety of grades. At the time of this writing the majority of the available research papers refer to the following three products:

- CarboDur (Sika Corporation),
- Forca Tow Sheet (Tonen Corporation)
- Replark (Mitsubishi).

The properties of these composite sheets are summarized in Table 2.1. The characteristics of the proprietary adhesives are summarized in section 2.2.1.

2.1.2. Comparison between FRP Sheets and Steel Plates

The strengthening technique of bonding steel plates is widespread around the world and is the state of the art. According to U. Meier from the Swiss Federal Laboratories for Materials Testing and Research (EMPA) for applications in which corrosion plays no role and the length of the strengthening component is less than 5 m., steel offers an optimum solution. However, in applications where corrosion, length of strengthening component and handling on construction sites play a dominant role, FRP laminate must be considered [EMPA- 01].

A comparison between CFRP sheets and steel plates in application to concrete structures is presented in Table 2.2. Part of the table is taken from references [SCD-1] and [EMPA-3].

Table 2.1 Data Summary For Commercial FRP

Property \ Product	Sika *CarboDur*	Tonen *Forca Tow Sheet*		Mitsubishi *Replark*
Type / Grades	Type 50 CarboDur Type 80 CarboDur Type 100 CarboDur	FTS-C1-20 FTS-C1-30 FTS-C5-30	FTS-GE-30 FTS-GT-30	Type 20 (MRK-M2-20) Type 30 (MRK-M2-30) Type MM (MRK-M4-20) Type HM (MRK-M6-30)
Type of Fibers	Carbon fibers Toray T300 &T700	High tensile CF High tensile CF High modulus CF	E-Glass Fibers T-Glass Fibers	Standard Modulus CF Standard Modulus CF Medium Modulus CF High Modulus CF
Type of Matrix	epoxy resin matrix	epoxy resin matrix	epoxy resin matrix	epoxy resin matrix
Tensile Strength	2,400 MPa (348 ksi)	3,480 MPa (505 ksi) 3,480 MPa (505 ksi) 2,942 MPa (427 ksi)	1,516 MPa (220 ksi) 2,694 MPa (391 ksi)	3,400 MPa (493 ksi) 3,400 MPa (493 ksi) 2,900 MPa (421 ksi) 1,900 MPa (276 ksi)
Modulus Of Elasticity 10^6 psi = Msi (1000 N/mm^2= 1 GPa)	.> 150 GPa (21.75 Msi)	230GPa (33 Msi) 230GPa (33 Msi) 373 GPa (54 Msi)	72.6 GPa (10 Msi) 87.1 GPa (12 Msi)	230 Gpa (33.4 Msi) 230 GPa (33.4 Msi) 390 GPa (56.6 Msi) 640 GPa (92.8 Msi)
Ultimate Elongation At Break [%]	1.4	1.5 1.5 0.8	2.1 3.2	N.A.
Fiber Areal Weight g/m^2 (oz/yd^2)	N.A.	200 (5.9) 300 (7.4) 300 (7.4)	300 (7.4) 300 (7.4)	200 (5.9) 300 (7.4) 300 (7.4) 300 (7.4)
Density ρ	1.6 g/cm^3 0.058 λβ/in^3	1.82 g/cm^3	2.55 g/cm^3 2.50 g/cm^3	1.6 g/cm^3
Thickness	1.2 mm	0.11 mm 0.17 mm 0.17 mm	0.118 mm 0.120 mm	0.11 mm 0.17 mm 0.17 mm 0.14 mm
Sheet width cm (inch)	50 mm (2.0") 80 mm (3.15")	50 cm (19.7") 50 cm (19.7") 50 cm (19.7")	50 cm (19.7") 50 cm (19.7")	25 cm (10") all grades 33 cm (13") all grades 50 cm (20") all grades
Proprietary Adhesive	Sikadur 30 - epoxy resin two component adhesive.	FP-NS, FP-NSS, FP-NSW, FP-S, FP-WE7, FP-WE7W, FR-E3P, FR-E3PS, FR-E3PW	FP-NS, FP-NSS, FP-NSW, FP-S, FP-WE7, FP-WE7W, FR-E3P, FR-E3PS, FR-E3PW	Epotherm Primer, Putty and Resin
Lengths Available	Any length	Standard:100 m.	Standard:100 m.	Standard: 100 m (328 ft)

Note: the values of properties are given in a sequence corresponding to grade sequence.

N.A. = Information not available

Table 2.2 Comparison of Strengthening Methods in Reinforced Concrete Structures

Criteria \ Material	FRP Laminate	Steel Plates
Own weight	Low. ρ=1.6 g/cm³	High. ρ=8.0 g/cm³
Strength of Material	Very high tensile strength in direction of fibers. Low strength in other directions (shear, delamination).	High strength in all directions.
Mechanical behavior	Brittle	Ductile
Fatigue properties	Outstanding.	Adequate
Overall thickness	Very low. Allows application of strips in multiple directions crossing each other.	Low
Length of strips/plates	Unlimited	Limited. Lap joints may be necessary.
Lap joints	Easy	Complex
Type of adhesive	Epoxy Resin	Epoxy Resin
Application techniques	No expensive equipment necessary. Especially convenient in case of overhead strengthening.	Lifting equipment and clamping devices necessary. Particularly inconvenient in case of overhead strengthening.
Handling	Easy. Flexible material. Can be applied on non-planar surfaces.	Difficult. Rigid material. Cannot be applied on non-planar surfaces.
Material costs	High	Low
Installation costs	Low	High
Corrosion	No corrosion. Alkali Resistant	Interface-corrosion
Durability	Depends on durability of adhesive. Protection against UV necessary.	Depends on durability of adhesive

2.1.3. Comparison Among Different Fibers

Fibers, natural or synthetic, are the fundamental constituent of a fiber-reinforced composite. They generally occupy the largest volume and are the major load carrying element of the composite. In this section, properties of typical fibers are presented. The type of fibers is limited to those that have a potential for application in construction [Az-06]

The choice of FRP material for use in a specific reinforcing application is dictated by the set of physical and mechanical properties of the fiber. Carbon Fiber based composites are the best performer in a majority of Civil Engineering applications because they fulfill most of the requirements (see Table 2.3, [EMPA-1]). Others types of fibers such as Glass and Aramid do not seem to satisfy durability requirements and therefore can not be used in cases where exposure to aggressive agents is expected.

Table 2.3 Qualitative Comparison of the Vulnerability of Different Fibers to Various Environments [EMPA-1].

Property \ Fiber	Carbon Fiber (CF)	Glass Fiber (GF)	Aramid Fiber (AF)
Vulnerable to Moisture	No	Yes	No
Vulnerable to Solvents	No	x	x
Vulnerable to Acids	No	Yes	Yes
Vulnerable to Bases	No	Yes	Yes
Vulnerable to UV radiation	x	x	Yes

2.1.4. Comparison Among Different FRP Sheets

Carbon, Aramid, and Glass fiber reinforced plastics are the three types of composite materials that dominate in Civil Engineering applications. The characteristics of a composite are dictated by the properties of the fiber and matrix as well as the method of fabrication involved and the structure of the composite itself.

Table 2.4 [EMPA-1], lists criteria which specifically relate to the use of composite materials as post-strengthening materials for structures. The table is also applicable to prestressed laminates (the FRP laminate is prestressed with initial force prior to be bonded to the reinforced concrete structure). From Table 2.4, it can be concluded that Carbon Fiber Reinforced polymer Composites are the most suitable for post strengthening of concrete structures.

Table 2.4 Comparison of Different Types of Fiber Reinforced Plastic Sheets [EMPA-1]

Property \ Fiber Sheet	Carbon Fiber (CF)	Glass Fiber (GF)	Aramid Fiber (AF)
Tensile Strength	Very good	Very good	Very good
Compressive Strength	Very good	Good	Inadequate
Modulus of Elasticity	Very good	Adequate	Good
Long Term Behavior	Very good	Adequate	Good
Fatigue Behavior	Excellent	Adequate	Good
Bulk Density	Good	Adequate	Excellent

2.2. Adhesives

Adhesives allow to bond structural elements without changing the appearance of the structure. Bond forces are generated by molecular attraction between adhesive and the bonded materials. The adhesive strength depends on the type of molecules and their reciprocal distance. It can be heavily diminished by factors like: dirt, oil , dust and grease. Therefore thorough preparation of surfaces is of utmost importance. Adhesion to exposed aggregates is generally better than to hardened cement paste.

Bonding with adhesive assures evenly distributed stress transmission over the whole contact interface, in contrast to anchorages such as bolted connections which create stress concentrations.

2.2.1. Properties of Commercial Adhesives

There is a number of companies on the market offering adhesives which are potentially suitable for use with FRP fabrics. Most of these adhesives are organic polymers (epoxy resins).

The following characteristics are considered essential for heavy duty structural adhesives:

- strong adhesion to bonded elements;

- strong cohesion;
- little tendency to creep under load;
- good resistance against humidity and alkalinity.

Epoxy resin adhesives possess dense cross links and meet the above requirements very well.

The main producers of FRP fabrics provide proprietary adhesives, which together with the FRP material create the system. The application of a specific type of adhesive depends on working conditions (temperature, moisture). The diversity of adhesives offer by the main producers of the sheets is as follows:

- Tonen Corporation (most diversified)
- Mitsubishi
- Sika Corporation (least diversified)

A comparison of adhesives from the leading producers is presented in Table 2.5 below.

Table 2.5 Comparison of Commercial Adhesives

Property \ Producer	Sika	Tonen									Mitsubishi						
Grade	Sikadur 30	FP-NS	FP-NSS	FP-NSW	FP-S	FP-WE7	FP-WE7W	FR-E3P	FR-E3PS	FR-E3PW	PS301	PS401	PS318	L525	L700S	L700W	L700R
Material	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy
Type	Adhesive Mortar	Primer Standard	Primer Summer	Primer Winter	Primer Penetr..	Primer Summer Damp Surf.	Primer Winter Damp Surf.	Resin Standard	Resin Summer	Resin Winter	Primer Fall/ Spring	Primer Spring/ Fall	Primer All year	Putty All year	Resin Spring/ Fall	Resin Winter	Resin Tunnel
Appl. Temp. °C (°F)	18-30 (65-85)	15-25 (59-77)	25-35 (77-95)	5-15 (41-59)	5-35 (41-95)	15-25 (59-77)	5-15 (41-59)	15-25 (59-77)	25-35 (77-95)	5-15 (41-59)	5-25 (41-77)	20-35 (68-95)	5-35 (41-95)	5-35 (41-95)	15-35 (59-95)	5-15 (41-59)	5-25 (41-77)
Mixing Ratio: by weight		2:1	2:1	2:1	1:1	2:1	2:1	2:1	2:1	2:1	2:1	2:1	2:1	2:1	2:1	2:1	2:1
by volume	3:1																
Viscosity, cps	N.A.	2,000	2,000	1,300	90	45,000	45,000	20,000	20,000	10,000	500 (MPa S)	500 (MPa S)	17 (MPa S)	Putty	4,000 (MPa S)	3,500 (MPa S)	4,000 (MPa S)
Pot Life, min @30°C (86°F)			40		120				40		25	140	> 120	30	50		
@23°C (73°F)	70										40	240	> 120	50	70	20	20
@20°C (68°F)		40	120	20	120	40	20	40	110	20							
@10°C (50°F)					120		50			50	95		> 120	100	-	70	70
Setting Time, hrs	N.A.																
@30°C (86°F)									7	7	-	4.0	-	3.0	3.5	-	-
@23°C (73°F)											3.5	7.0	2.5	3.5	6.0	3.5	3.5
@20°C (68°F)		10	12	7	3	12	10	10	12	12	-	-	-	-	-	-	-
@10°C (50°F)											6.5	-	4.0	5.0	-	6.0	6.0
Couring Time, days @30°C (86°F) @23°C (73°F) @20°C (68°F) @10°C (50°F)	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	5 7 - -	- - 7 14	- - 7 14
Compressive Strength (14 day) MPa (psi)	> 58.6 (8,500)	N.A.									N.A.						
Shear Strength MPa (psi)	24.8 (3,600)	12.5 MPa									N.A.						
Tensile Strength (7 day), MPa (psi)	24.8 (3,600)	N.A.									N.A.						
Elong. at Break	1%	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.

Property \ Producer	Sika	Tonen									Mitsubishi						
Grade	Sikadur 30	FP-NS	FP-NSS	FP-NSW	FP-S	FP-WE7	FP-WE7W	FR-E3P	FR-E3PS	FR-E3PW	PS301	PS401	PS318	L525	L700S	L700W	L700R
Bond Strength: - Concrete to conc. - Concrete to steel	21.3 MPA 17.9 MPA	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Shelf Life	2 years in unopened packaging	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Storage Conditions °C (°F)	4-35°C (40-95°F)	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Color Main Agent Hardener	Light gray	N.A.									Pale yellow Brown		Transp. Brown	White Black	Green and thixotropic liquid Brown		

N.A. = Information not available

2.2.2. Research on Adhesives

The mechanical properties of the adhesive used for this particular type of repair system will influence the overall behavior of the strengthened structure, particularly, the strength and durability of the interface layer. Most of the experimental work so far undertaken confirm, that the commercial systems present a failure in the concrete cover rather than in the adhesive interface. This proves that the adhesive posses a sufficient strength. Durability of the interface constitute a major concern and requires further investigation.

Saadatmanesh and Ehsani [AZ-3, AZ-5] studied the behavior of four different types of epoxies, used to glue GFRP sheets for strengthening of concrete beams. Five beams were tested to find the static flexural strength. Four beams were strengthened with GFRP sheets using different epoxies, the fifth was not strengthened and used as a control specimen. Two modes of failure of strengthened beams were recognized: failure of the plate (yielding of steel plate or rupture of fiber composite plate and crushing of concrete in compression) and shear failure of the adhesive concrete layer. It was also found that the maximum achievable force in the plate at failure will be equal to the resultant of the limiting shear stresses. It was concluded that selection of a suitable epoxy is very important in the success of this strengthening technique. The epoxy should have sufficient stiffness and strength to transfer the shear force between the composite plate and concrete. It should also be tough enough to prevent brittle bond failure as a result of cracking of concrete. Rubber toughened epoxies were found to be particularly suitable for this application.

2.3. Comparison of Different CFRP Systems

A comparison of the properties and applicability of different strengthening systems is presented in Tables 2.6 and 2.7. Tonen Forca Tow sheet, Mitsubishi Replark and Sika CarboDur are the three type of commercial systems considered. Mechanical properties and durability data are presented. The tables were developed following analysis of technical data provided by the suppliers.

Table 2.6 Comparison of Properties of Different Strengthening Systems

Supplier		Tonen			Mitsuibishi				Sika
System		Forca Tow Sheet			Replark				CarboDur
CFRP Sheet	Type	FTS-C1-20	FTS-C1-30	FTS-C5-30	MRK-M2-20	MRK-M2-30	MRK-M4-30	MRK-M6-30	CarboDur Strip
	Tensile Strength (MPa)	3,480	3,480	2,942	3,400	3,400	2,900	1,900	2,400 10³
	Tensile Modulus (GPa)	230	230	373	230	230	390	640	1050
	Thickness[a] (mm)	0.11	0.17	0.17	0.118	0.17	0.17	0.14	1.2
	Ultimate Elongation (%)	1.5	1.5	0.8	N.A.	N.A.	N.A.	N.A.	1.4
	Width	50 cm			25 cm, 33 cm, 50 cm				5 cm, 8 cm cm2",3.2",4"
	Length	100 m Standard			100 m standard				Up to 250 m
Epoxy	Type	FR-E3P (Resin)	FR-E3PS (Resin)	FR-E3PW (Resin)	L700S		L700W	L700R	Sikadur 30
	Application Temperature(°C)	Standard (15°-25°)	Summer (25°-35°)	Winter (4°-15°)	Spring to Fall (15°-35°)		Winter (4°-15°)	Tunnel (5°-25°)	≥39°
	Tensile Strength	N.A.	N.A.	N.A.	N.A.		N.A.	N.A.	24.8 MPa
	Elastic Modulus	N.A.	N.A.	N.A.	N.A.		N.A.	N.A.	4.48 MPa
	Elongation	N.A.	N.A.	N.A.	N.A.		N.A.	N.A.	1%
	Shear Strength	N.A.	N.A.	N.A.	N.A.		N.A.	N.A.	24.8 MPa
	Shrinkage	N.A.	N.A.	N.A.	N.A.		N.A.	N.A.	0.0004
	Pot Life (min.)	40	110	20	70		20	20	70
	Viscosity (cps)	20,000	20,000	10,000	4,000 MPa S		3,500 MPa S	4,000 MPa	N.A.
Primer	Type	Standard, Summer, Winter, Penetrative, Summer Damp Surface, Winter Damp Surface			Fall to Spring, Spring to Fall, All year				No Primer

a: Total cross sectional area of fibers per inch.
N.A.= Information not available

Table 2.7 Comparison of Applicability of Different Strengthening Systems

System / Category	Tonen *Forca Tow Sheet*	Mitsuibishi *Replark*	Sika *CarboDur*
CFRP Sheet	- Easy control of strengthening level with layer -Thin thickness:0.0065in.(0.17mm) (3.3 kips/in.) > For bending strengthening . Slab, box beam: 1-2 layers . I or T beams: 3 to 5 layers > For shear strengthening . Easy wrapping of beam . Sufficient anchorage for shear	Same as Tonen Forca Tow Sheet	- Control of strengthening with strip - Thick thickness: 0.047in (1.19mm) (16.4 kips/in.) > For bending strengthening . Slab, box beam: several strips (only 1 layer) . I or T beams: only 1 layer . Require higher shear interface > For shear strengthening. . Impossibility of wrapping . Insufficient anchorage
Epoxy & Primer	Wide selection of resin systems (4 epoxies & 6 primers) suitable for various concrete surfaces and climate conditions	- 2 epoxies and 3 primers for different climate conditions	- Wide coverage of applicability of the resin,Sikadur-30 (> 39°F) - Tolerant of moisture before, during, and after cure - No primer is needed
Field Applications	- 120 field applications in Japan - Foulk Road Bridge (box beam), Delaware	-16 field applications - Bridge girder, Florida	- Applications in Europe - Ibach bridge (box beam), Switzerland
Research Programs	- University of Delaware (with Delaware DOT) - West Virginia University - Federal Highway Administration - University of California (with US Navy Engineering Service Center) - Caltrans	- Caltrans - Federal Highway Administration in McLean and Florida - Florida DOT - Georgia Institute of Technology	- EMPA (Federal Materials Testing and Research Center), Switzerland since 1984

CHAPTER 3
APPLICATION PROCEDURES

This chapter presents the synthesis and the comparison of the application procedures based on the information extracted from different commercial and research sources. In case of use of a particular FRP system, the application procedure provided by the material supplier should be followed.

3.1. Assessment of Existing Conditions

The determination of strengthening technique should be supported by thorough examination of existing structural and environmental conditions such as:

- Conditions of the member;
- Concrete quality;
- Reinforcement configuration and location;
- Member geometry;
- Load conditions;
- Environmental exposition (Road salt, UV light, freeze-thaw).

3.2. Surface Preparation

The bond strength between the adhesive and the materials depends on the type of molecules and their reciprocal distance. Dirt, dust, oil and grease heavily impair the reciprocal attraction. Most engineers tend to focus on achievement of the prescribed initial bond strength. However, bond properties are dictated by environmental stability of the adherent-adhesive interface. This is in particular true in civil engineering applications, where degree of control is limited, and the vagaries of nature such as extreme temperature, moisture, sustained and cyclic loading are very intense.

Therefore, thorough preparation of the surfaces of the parts bonded together is of great importance. The FRP can be applied on sound and clean surfaces. The suppliers of FRP prescribe the necessary actions to achieve suitable surface conditions. The following represents the synthesis of the surface preparation recommendations taken from commercial information and also the research sources. Before application of a particular system, one should refer to the appropriate commercial specifications. All possible bonding surfaces involved in strengthening system (concrete, FRP, steel) should be prepared.

3.2.1. Concrete Surfaces

- In order to provide open roughened texture the application of the following surface preparation techniques can be necessary:
  - Sandblasting (high pressure sand abrading);
  - High-pressure water washing;
  - Bush-hammering;
  - Disk abrading (grinding).
- Surface must be free of standing water. Some types of adhesives require dry surface.
- Watch for the formation of condensation (dew point).
- Removal of dust (vacuum cleaning).
- Removal of grease, curing compounds, impregnation, waxes, foreign particles, disintegrated materials, paints, plasters, wall papers and other bond inhibiting materials.
- Adhesion to exposed aggregates is generally better than to the hardened cement paste. The laitance must therefore be removed and the aggregate must be exposed as gently as possible.
- Filling of gaps, cavities and uneven portions of structure with appropriate repair mortar specified by the system producer. According to Sika AG, an epoxy repair mortar should be apply ([SCD-1]).
- The surface to be coated must be even (on a length of 2 meters, unevenness may not exceed 10 mm [SCD-1]). Steps and formwork marks should not be greater than 0.5mm.
- At the direction of the engineer, the adhesive strength of the concrete surface should be verified after preparation by random pull-off testing (ACI 503R). This testing should prove a minimum tensile strength of the adhesive interface specified by the system supplier.

The comparison of different surface preparation techniques depending on the level of contamination and deterioration and the depth of removal of concrete cover is presented in the Table 3.1 below (based on Sika materials.) The bigger the contamination and the thickness of removed material the more aggressive is the method that have to be applied.

Table 3.1 Methods of Concrete Surface Preparation

Preferred use for the surface conditions below	Method
Removal of oils, greases, proteins (water-soluble, agents water-emulsive)	Steam jets with added wetting agents
Removal of old paint	Steam jets with added wetting agents and sand
Removal of old paint, heavy contamination on low-strength surface areas of the concrete, damage from the road salts	Sand-blasting, Water sand-blasting, High pressure water-jets
Removal of thicker old coatings from deeper areas with low surface strength, deep-reaching contamination	Flame-cleaning and mechanical cleaning
Removal of deep-reaching road salts and other contamination.	Grinding and mechanical cleaning

The optimum roughness of substrate (0.5-1.0 mm) can be achieved with sandblasting technique [SCD-1]. Protruding arises, remains from shuttering, dowels etc. must be removed. Visual check of the treated substrate surface for foreign matter and inclusions in the concrete is part of quality control.

3.2.2. Steel Surfaces

- Removal of grease, oil, rust and scale;
- Preparation - sandblasting;
- Watch for the formation of condensation (dew point);
- If not bonded immediately, the surface has to be protected with compatible corrosion inhibitor.

3.2.3. FRP Sheets

- Place FRP fabric on even surface (such as table).
- Check the material for possible damages, cracks etc.
- The CFRP strips have to be cut to proper length by metal saw or disk-cutter before application.
- Sika recommends to wipe clean with appropriate cleaner (e.g. acetone). This operation removes soiling as well as carbon dust. Cleaning should be continued until white cloth remains white.
- Dry CFRP laminate with a clean rag (Sika)

3.3. Mixing of Adhesives

- Consult technical data sheet for specific type of adhesive.
- Protect adhesive and components from direct sunlight.
- Maintain appropriate proportions of components. (parts by weight or parts by volume).
- Prepare only that quantity which can be used within its pot life.
- Premix each component in the original containers.
- Consult technical data sheet which component should be added to which. Generally hardening component is added to resin component.
- Mix the adhesive until uniform in consistency (uniform color). Use electric hand mixer for about 3 minutes or mix manually with the trowel or spatula. Mix with low speed so that as little air as possible is entrained (max. 500 rpm).
- Take care to scrape the sides of the pail during mixing.
- The pot life of the adhesive begins when the resin and hardener are mixed.
- To obtain longer workability and pot life the following suggestions can be followed:
  - Pot life is longer at lower temperatures. If necessary the adhesive components can be chilled to room temperature before mixing.
  - Adhesive prepared in smaller quantities has usually longer pot life.

3.4. Application to Structure

- If the system being used requires the primer (Tonen, Mitsubishi), apply according to commercial specifications.
- Apply the mixed adhesive onto the concrete with trowel, float or spatula to form a layer of required thickness.
- The adhesive has to be applied with great care to the concrete surface to ensure that all the voids are filled and no cavities are left.
- Apply the mixed adhesive onto the CFRP laminate to form a layer of required thickness.
- Within the open time of the adhesive, depending on the temperature, place the FRP onto the concrete surface.
- Press the laminate into the adhesive using the hard rubber roller until the adhesive is forced out on the sheet sides.
- Remove excess adhesive.
- Leave the applied layer undisturbed for at least 24 hours.
- Repeat the application process for desired number of layers. Maintain proper width of glue line.
- Apply coating for protective or aesthetic finish (optional).
- During the curing time of the adhesive heavy traffic loads should be regulated in order to avoid a possible diminution of the bond strength of the adhesive to the concrete surface.

3.5. Additional Limitations and Requirements

- Consider that FRP materials are easily damaged in transport or in the field by cutting, bending , and trampling.
- The minimum age of concrete must fulfill the requirements of a particular system. In most cases, it should be 21-28 days unless special curing and drying conditions are provided.
- Do not thin the adhesive unless specified. Solvents will prevent proper curing.
- CFRP material is a vapor barrier after cure.
- Minimum substrate and ambient temperature depends on type of adhesive used. It has to be checked with data sheet.
- In extreme solar radiation, most cold-setting epoxy adhesives experience a reduction of shear modulus and shear strength.

3.6. Safety Precautions and First Aid

Safety Precautions - Basic Measures.

- Consults the material safety data sheet for the adhesive before application.
- Epoxy resins can cause skin sensitization or irritation (dermatosis) after prolonged or repeated contact. They can also be eye irritant or even cause burns.

- High concentration of vapor may cause respiratory irritation. Therefore adequate ventilation is necessary. Overexposure may affect liver, kidney, and/or central nervous system effects.
- Use of standard precautions such as safety goggles and chemical resistant gloves is recommended. Cover hands with barrier cream before starting work.
- In any case avoid contact and limit exposure to a necessary minimum.
- In case of skin contact wash immediately and thoroughly with soap and water. Contact physician if symptoms persist.
- In case of eye contact wash immediately with plenty of water for at least 15 minutes. Immediately contact physician.
- In case of respiratory problems, remove person to fresh air. Contact physician if symptoms persist..
- In case of respiratory overexposure (excess of PELs) use the appropriate, properly fitted NIOSH/MSHA approved respirator.
- If sanded , possible exposure to crystalline silica (sand) dust may cause delayed lung injury and is listed as a suspect carcinogen by NTP and IARC. Use of appropriate dust protection is recommended.

Safety Precautions - Additional Measures.

- In case of spills or leaks, wear suitable protective equipment, contain spill, collect with absorbent material and transfer to suitable container. Ensure proper ventilation of the area.
- Uncured material can be removed with approved solvent.
- Cured material can only be removed mechanically.
- Dispose of in accordance with current, applicable local, state and federal regulations.
- Unused adhesives should not be discharged into drains, waterways or ground.
- Keep materials out of reach of children.

3.7. Commercial Systems - Comparison of Application Procedures

Table 3.2 provides the comparison of application procedures for the three main strengthening systems evaluated here.

Table 3.2 Comparison of Commercial Application Procedures

Procedure	Sika *SikaDur*	Tonen Forca Tow Sheet	Mitsubishi *Replark*
FRP Cleaning	Yes (required)	Yes (required)	Yes (required)
Concrete Water Jet	Yes (allowed)	Yes (experiment)	Yes (experiment)
Concrete Sandblasting	Yes (required)	Yes (experiment)	Yes (experiment)
Concrete Grinding	Optional	Yes (required)	Yes (required)
Priming	No	Yes	Yes
Putty (Filler) application	Yes SikaDur 41	Yes	Optional
Undercoating - 1st Resin Coating for 1st and further plies	Yes	Yes	Yes
Protective overcoating - 2nd Resin Coating	No	Yes	Yes
Finishing and Painting	Optional	Optional	Yes

3.7.1. Conditions of Service

Considerations of safety may be determined for the conditions of service of the strengthened structure:

- For whatever reason a laminate fails, it is necessary to ensure that the consequential damage can be assessed and no safety risks are incurred. According to U. Meier a post-strengthened structure should continue to have a total safety of 1.2 after laminate failure [EMPA-03].
- Recording of the condition of the structure requiring strengthening is important. Dimensions, quality of the existing construction, materials and ambient conditions must be established.
- The fact that CFRP laminates have no plastic deformation reserve, must be allowed for in the calculation of the load bearing capacity with an appropriate reduction factor less than that for steel members. The engineer can maximize the ultimate load of the full system by appropriate selection of the strengthening level in the critical sections.
- Bending failure in a conventional reinforcement concrete structure is generally preceded by serious deformation and wide cracks, but advance warning of imminent laminate failure in a post-strengthened structure has to be obtained in some other way.

CHAPTER 4
REVIEW OF RESEARCH AND FIELD APPLICATIONS

4.1. Introduction

Different types of unidirectional and bi-directional FRP sheets made of Carbon (CFRP), Glass (GFRP) or Aramid (ARFP) fibers are used both in research and applications for strengthening and repair of existing structures. They are used as a substitute for steel plates. FRP sheets possess a number of features that make them suitable for such applications:

- good mechanical properties;
- low volume to weight ratio;
- immunity to corrosion;
- no need for the formation of joints (practically unlimited delivery length of FRP).

The research projects carried out at different organizations were aimed at various aspects of strengthening concrete structures:

- bonding of fiber-reinforced plastic composite plates or fabrics to reinforced concrete and prestressed concrete beams to improve flexural stiffness and strength;
- wrapping of concrete beams with composite fabric/epoxy jackets to provide additional shear strength;
- wrapping of concrete columns with fiberglass/epoxy jackets to provide the additional flexural stiffness and strength, in particular for seismic retrofit;
- confinement of concrete columns to increase column ductility as well as load capacity.

Typical applications of FRP for strengthening RC and PC beams for flexure and shear are given in Figure 4.1.

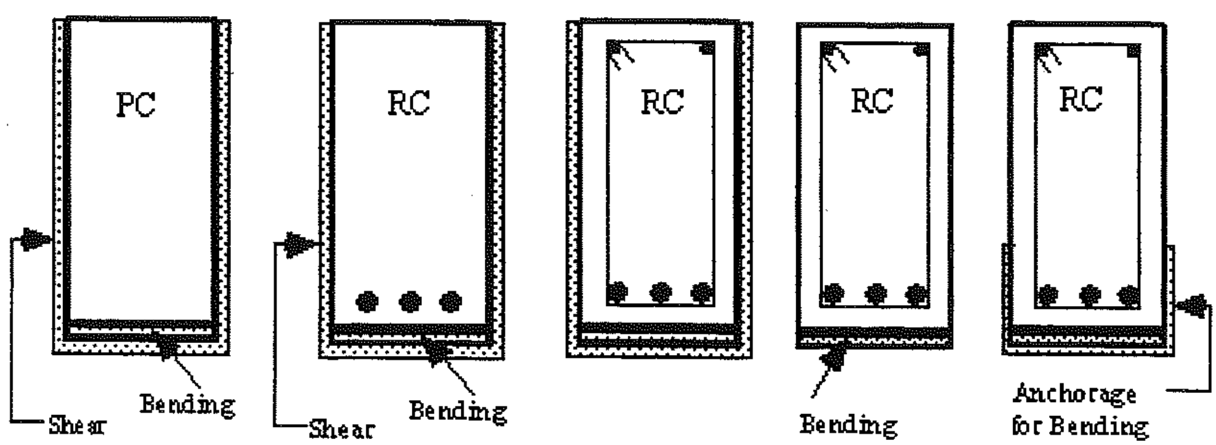

Figure 4.1 Typical Applications of Glued-on FRP Composites for Shear

PC = Prestress Concrete, RC = Reinforced Concrete

A review of research issues on the use of FRPs can be found in references: [SOA-1], [CA-1], [XX-7], [XX-12]. This report is devoted to the first and second aspects - strengthening of the beams in flexure. A summary of the reviewed research on strengthening of beams (structures) in flexure is presented in Table 4.1 for quick reference. The literature about FRP addresses the following topics:

- Structural behavior (Flexural behavior; Shear, Fatigue, Bond);
- Durability (freeze-thaw, chemical aggression, low temperature, UV light, fire resistance);
- Field applications and demonstrations.

The following sections give summary of literature for each of the topics with division into categories. Field demonstrations are in most cases performed on real structures and therefore no failure information is provided. The results are limited to visual and electronic monitoring of the structures.

4.2. Structural Behavior

This section reviews structural features and significant issues of this new construction technology. It covers different strengthening systems (CFRP, GFRP AFRP, steel plates) and their comparison.

The structural behavior of laminate bonded beams depend on many variables. Successful implementation of the technology is strictly dependent on maintaining the highest possible standards and compliance with the requirements of a particular strengthening system. The following list of factors to consider, as taken from [X-12], is not exhaustive, but indicates the complexity of the issue and the scope of the literature.

- Geometry of the beam;
- Mechanical properties of the concrete of the beam (compressive strength, modulus of elasticity);
- Geometrical properties of the FRP laminate: (thickness, area);
- Mechanical properties of the FRP laminate (tensile strength, modulus of elasticity);
- Type of composite (Carbon - CFRP, Glass - GFRP, Aramid - AFRP);
- Type of primer and adhesive;
- Surface preparation procedures;
- Composite application procedures;
- Loading (static, dynamic);
- Beam reinforcement (under-reinforced, over-reinforced, prestressed);
- Beam state of cracking;
- Exposition to environmental actions: (corrosion, weather, freeze/thaw, sun light, aging);
- Bond of the interface between the FRP plate and concrete.

Table 4.1 Summary of FRP Literature by Organization or Research Team

Institution	Research Team	Type & Grade of FRP (other reinf. systems), Adhesives	Laboratory Tests	Field Tests, Demonstrations, Applications	Reference Code	References
Sika		CarboDur			SCD	SCD
Tonen Corporation, H.S. Kliger & Associates, Structural Preservation Systems	Akira Kobayashi , Ohori N., Hiroyuki Kuroda, Hiroyuki Yoshizawa , Howard S. Kliger, Jay Thomas,	CFRP - Forca Tow Sheet	Bonding strength tests, Concrete beams, 4-point bending, Flexural capacity, Fatigue of slabs	RC-slab in highway bridges (FTS-1-3).	FTS	FTS-1-6
Mitsubishi , Craig Ballinger & Associates	Moriyasu Nakamura Hiromichi Sakai Kensuke Yagi Tsunego Tanaka Craig Ballinger T. Maeda T. Hoshijima	Replark, High Modulus CF - E65, Inter Modulus CF - E24	Concrete beams, 4-point bending, Flexural capacity		MRK	MRK-1-3
Ohio DOT, Wright Patterson Air Force Base	Steven E.Morton John Mistretta Karen R. Schaefer	AS4C/1919 Hercules Inc.	Tensile test of fiber material, Concrete & steel adhesive bond test, 4-point bending of Concrete & steel beams, Freeze thaw tests, Fatigue tests	Butler County Ohio - RC bridge	OH	OH-1-2
Ohio State University, Wright Patterson Air Force Base	Muszynski L.C., Sierakowski R.L.	AS4C/1919 Hercules Inc.	Concrete beams, Fatigue tests, Three-point bending		OH	OH-3
Deleware DOT, University of Deleware	Michael Chajes William W. Finch Ted F. Januszka Dennis R. Mertz Chao Hu Cory A.Farschman Theodore A.Thomson	Carbon Fiber, E-Glass Fiber, Aramid Fiber (Kevlar), CFRP - Tonen, SikaDur 32	Concrete beams, 4-point bending, Flexural capacity, Freeze/thaw tests, Dry/wet tests, Fatigue tests	Foulk Road Bridge #26, Wilmington, Delaware.	DE	DE-1-3

Institution	Research Team	Type & Grade of FRP (other reinf. systems), Adhesives	Laboratory Tests	Field Tests, Demonstrations, Applications	Reference Code	References
Swiss Federal Laboratories for Materials and Testing, EMPA	Urs Meier Gregor Schwegler Martin Deuring	GFRP plates CFRP plates T300 T700 fibers	Concrete beams Bending, Flexural capacity Freeze-thaw tests Fatigue tests Durability (Fire tests)	Kattenbush bridge Ibach bridge, Switzerland	EMPA	EMPA-1-12
University of Arizona	Hamid Saadatmanesh Mohhamad R Ehsani	GFRP plates CFRP plates	Prestressing of plates before testing 4-point bending Analytical models Testing of epoxies		AZ	AZ-1-11
RUTGERS The State Univ. of New Jersey	P.Balaguru Stephen Kurtz Jon Rudolph	Carbon Fiber T300, Geopolymer	4-point bending, Concrete beams (4 pc), Flexural strength		RNJ	RNJ-1-2
West Virginia University, Constructed Facilities Center	Hota V.S. GangaRao, Salem S. Faza, Ever J. Barbero	CFRP - Tonen FTS-C1-20, Steel plates	4-point bending Concrete beams (21pcs), Flexural strength		WVU	WVU-1-3
Universite de Sherbrooke (Canada)	M'Bazaa I., Missihoun M., Labossiere P.,	CFRP - Tonen FTS	4-point bending Concrete beams (8 pcs), Flexural strength		XX	XX-1
Naval Facilities Engineering Service Center, University of California	Malvar L.J., Warren G.E., Inaba C.	CFRP - Tonen FTS-C1-20	3-point bending, Concrete beams (6 pcs), Flexural strength, Shear strength. Square slabs (6pcs), Punching shear		XX	XX-2-3
King Fahd University of Petroleum and Minerals	Sharif A., Al-Sulaimani G.J., Basunbul I.A., Baluch M.H., Ghaleb B.N.	CFRP plates	Concrete beams (10 pcs), 4-point bending		XX	XX-5-6
University of Wyoming	Prof. Charles Dolan				UWY	
University of California	Prof. Frieder Seible				CA	
New Jersey Institute of Technology	dr William Spillers					
Pennsylvania State University	Antonio Nanni				PSU	
Lawrence Technological Institute	Prof.Nabil F.Grace					
Georgia Institute of Technology	Abdul-Hamid Zureick				GAT	
FDOT Florida DOT	Mohsen Shahawy				FL	FL-1

Institution	Research Team	Type & Grade of FRP (other reinf. systems), Adhesives	Laboratory Tests	Field Tests, Demonstrations, Applications	Reference Code	References
CDOT California DOT	Mosen Soltan				CA	CA-1-2
US Corps of Engineers	Edward O'Neil				USCE	
US Corps of Engineers	Jonathon Trovillion					
FHWA Federal Highway Administration	Eric Munley				FHWA	FHWA
Catholic University	Lawrence Bank					

The bond between the composite and concrete substrate has a significant role in structural characteristics of the reinforced members. The influences of bond can be classified as follows [CA-1]:

Internal influences:	Chemical Activity Electrochemical activity Alkali content and pH level Stress Moisture infiltration Transport of solutions, salts
Interfacial influences:	Moisture entrapment Moisture diffusion Selective transport of chemicals Thermal and elastic mismatch
External influences:	Humidity Moisture Temperature Temperature Cycling (daily, seasonal, annual) Aggressive natural and manmade agents UV light Oxygen (related to steel)

The dominant mechanism of bond in FRP reinforced structures is by mechanical interlock. The rough and deep surface topography created through surface abrasion creates a structural morphology that allows the resin to penetrate into irregularities forming a strong interfacial layer [CA-1].

4.2.1. Modes of Failure of Post-strengthened Beams

There are different modes of failure of beams post-strengthened with FRP. Depending on the particular design of the beam the failure of the FRP system can cause immediate failure of the member or influence its reliability. The modes of failure depend on the factors listed in the previous section. Some modes are more probable than other. The possible failure modes are:

a. Failures of concrete
   - (CC) - Failure of concrete compressive zone when the maximum concrete compressive stress is reached.
   - (CS) - Vertical shear failure of concrete.
   - (CP) - Punching shear.

- (CD) - Failure of concrete cover (delamination in concrete)

b. Failures of Reinforcing Steel
   - (RT) - Failure of reinforcing bars - yield strain exceeded.
   - (RF) - Fatigue failure of reinforcing bars - fatigue strength exceeded.

c. Failures of FRP laminates
   - (FT) - Failure of FRP laminate when tensile strength is reached.
   - (FD) - Inter-laminar failure of the laminate (delamination in FRP).
   - (FC) - Failure of FRP material caused by transverse reciprocal displacement of crack edges at the bottom of the beam.

d. Failure in adhesive surface
   - (BF) - Adhesion failure (FRP-concrete surface).

The above codes for failure modes are utilized throughout the report. The examples of the most typical failure modes are illustrated in Figure 4.2.

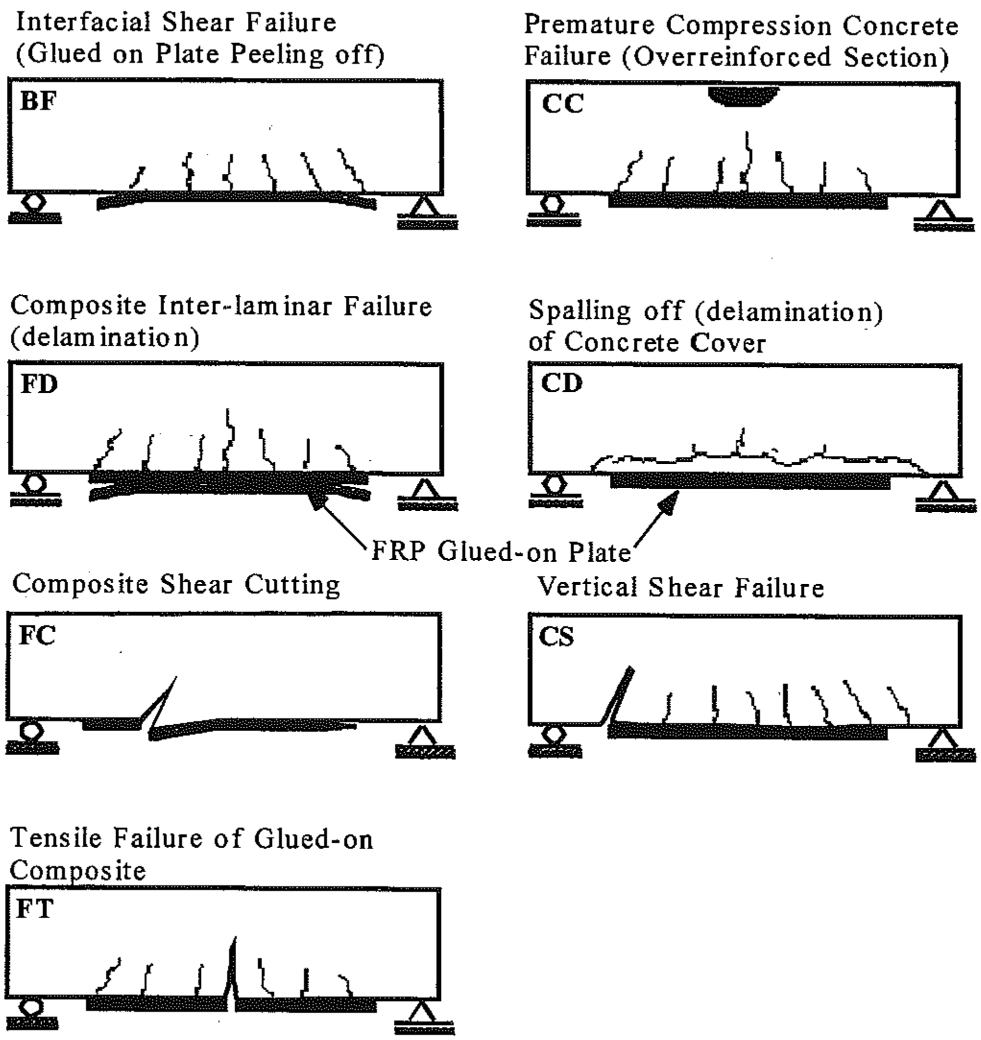

Figure 4.2 Typical Failure Modes of RC and PC Beams Strengthened with FRP

4.3. Flexural Behavior

FRP sheets used for strengthening the flexural capacity of concrete elements reveal their great potential thanks to their strength and stiffness. This results in a relatively low cost of repair.

In the majority of flexural applications, unidirectional sheets prove to be good performers in strengthening the mid span section of reinforced and prestressed concrete beams. In cases of complex states of stress such as bending combined with shear, two or multidirectional composite fiber laminates have to be used

The following sections summarize the experimental works focused on the flexural behavior of FRP strengthened concrete elements The information covered is classified according to its source.

4.3.1. FTS - Tonen Corp., H.S. Kliger & Associates, Structural Preservation Systems

References: [FTS-1][FTS-2]

The experimental program was carried out to investigate the flexural strength of reinforced concrete beams post-strengthened with CFRP. The unidirectional fabrics were glued to the tension face of the beams. Total of ten beams were tested. Forca Tow Sheet FTS-C1-30 & FTS-C5-30 was used as the bottom strengthening. One of the beams was strengthened with steel plate and one control beam had no external strengthening. The wrapping with FTS at 90 deg angle was done in some beams to investigate the influence of anchoring on failure mode. It was observed that the Tow Sheet increased the yield load in the beam in comparison to control case, regardless of the sheet angle and/or number of plies applied. The increase of yield load varied from 91% to 158%, for one and three plies of fabric respectively. The mode of failure depended on the particular beam. In the beams having the anchoring by 90 deg wrapping of longitudinal fabrics no peel-off effect was observed. Due to the use of this type of anchoring the ultimate strength of beams was maximized and increased by 207% over the bare beam. Other samples exhibited the peel-off in cohesive layer of concrete. The comparison of the experimental results with theoretical predictions proved good agreement.

Reference: [FTS-5]

The experimental program was carried out to investigate the flexural strength of reinforced concrete beams post-strengthened with CFRP. The main purpose was to investigate the influence of surface preparation on the effect of strengthening. The unidirectional fabrics were glued to the tension face of the beams. Total of eight beams were tested. In general CFRP increased yield load of beams in comparison to unreinforced (control) beam. The maximum load is greatly influenced by concrete surface treatment. The beams treated with water jet performed significantly better than the beams treated with sander. The increase of maximum load due to CFRP equaled accordingly 70-80% for the beams treated with water jet and 30-40% for those treated with sander. It was concluded that water jet treatment is a very effective way of surface preparation.

4.3.2. MRK - Mitsubishi (Replark), Craig Ballinger & Associates

Reference: [MRK-1]

A series of bending tests was carried out on rectangular reinforced concrete beams in four point setup. Two different types of CFRP sheets were used: High-Modulus E65 and Inter-Modulus E24 (general-purpose). The unidirectional fabrics were glued to the tension face of the beams. One and two-layer strengthening was selected. Strain gauges monitored the deformation of specimens. The tests revealed that in comparison to non-reinforced beam, the crack occurrence load was improved by 32% with one ply and 72% with two plies for the Inter-Modulus CF, and by 88% with one ply and 120% with two plies of High-Modulus CF. Comparing to non-reinforced beam, the maximum load was improved by 40% with one ply and 71% with two plies for the Inter-Modulus CF, and by 42% with one ply and 82% with two plies of High-Modulus CF. Flexural rigidity increased by 24% with one ply and 31% with two plies for the Inter-Modulus CF, and by 50% with one ply and 91% with two plies of High-Modulus CF. The sheet with the higher Young's modulus has higher reinforcing effect. The comparison of calculation methods and results of computations proved good agreement. It was concluded that the procedure for design of RC-beams with CFRP reinforcement should assume the following order of failure:

- Yield of tension reinforcement,
- CFRP sheet breakage,
- Crushing failure of concrete.

4.3.3. AZ -University of Arizona

References: [AZ-01][AZ-03]

Saadatmanesh, H and Ehsani, M.R. presented the experimental study of 5 rectangular beams and one T-beam strengthened by gluing GFRP plates to their tension flanges and tested under 4 point bending. Based on the results of an earlier study, a rubber-toughened epoxy with a consistency similar to that of cement paste was used for strengthening of the beams. As a result of this study, it was concluded that a significant increase in flexural strength can be achieved by bonding GFRP plates to the tension face of reinforced concrete beams. The gain in ultimate flexural strength was more significant with lower steel reinforcement ratios. In addition, plating reduced crack size in the beams at all load levels but also reduce the ductility of the beams. The successful application of this technique requires careful preparation of the concrete surface and selection of a tough epoxy. Finally, calculated load-deflection curves were obtained using the strain compatibility method. Compared with the measured load-deflection curves, they correlated well.

Reference: [AZ-2]

Char M.S., Saadatmanesh, H and Ehsani, M.R conducted a parametric study of the flexural strength of concrete girders externally prestressed with epoxy bonded fiber reinforced plastic (FRP).Variables considered are type of FRP plate, area of plate, and concrete compressive strength. The girders were externally prestressed with FRP plates epoxy bonded to the tension face of the girders, while the girders were held cambered by means of upward jacking forces. As a final step, a design example is presented showing how this technique can upgrade the load carrying capacity of a typical concrete bridge originally designed for H15 loading to that of HS20 loading.

For this study, analytical models are presented to calculate moment and curvature for concrete girders externally prestressed with GFRP plates throughout the entire range of loading up to failure. Conclusions of this study are :

- Bonding a FRP plate to the tension face results in a significant increase in the moment carrying capacity of the girder.
- Increasing the area of the plate from 4 to 8 in further increased the moment carrying capacity of the section.
- The behavior of the beam with camber is similar of the one with no camber. The moment capacity of the beam remains the same.
- The higher tensile strength of the CFRP plate resulted in a significantly greater increase in the moment capacity compared to that for the GFRP plate. However, the ductility of the beam is reduced due to the greater stiffness of the CFRP plate.
- On the design example, stresses in beams strengthened with GFRP and CFRP plates without camber are slightly higher than the allowable stresses as provided by AASHTO specifications. The externally prestressed beams satisfy the AASHTO allowable stress requirements.
- Beams that have been strengthened for flexure may fail in shear. Flexural strengthening may require that the shear strength of the beam be increased as well.

4.3.4. DE - University of Delaware, Delaware Department of Transportation

Reference: [DE-1]

At the University of Delaware the tests were performed on 14 rectangular under-reinforced concrete beams. The experiments were aimed at evaluation of the effect of externally bonded, composite FRP sheets on the beams flexural behavior. Different types of FRP were used (CFRP, GFRP, AFRP). The four-point bending setup was used with load increased monotonically to failure. The general flexural behavior of the composite-fabric-reinforced beams was similar, although the flexural stiffness and final mode of failure varied depending on the used type of fabric. Beams reinforced with fabrics displayed less ductility compared to the beams reinforced with steel alone, however they exhibit some measure of ductility prior to failure. All the externally reinforced beams showed significant increases in ultimate flexural capacity, as compared with control beams, within the range 33.6 to 57%. Also the average stiffness of the specimens increased within the range 45 to 53.2%. Parallel to experiments the analytical model for calculation of beam capacity was developed giving the results close to test values. The results of the study indicate that the externally applied reinforcement can be effectively used to rehabilitate or strengthen the concrete beams. The analytical methods to describe their behavior are available. The bond between the fabric and the concrete, combined with the additional anchorage ensured the failure of either the concrete in compression or the fabric in tension.

4.3.5. RNJ - RUTGERS The State Univ. of New Jersey, GEOPOLYMERE

Reference: [RNJ-1]

The tests of flexural strength of beams carried at the RUTGERS University of New Jersey were aimed and checking the application of carbon fiber and geoplymer adhesive. The unidirectional fabrics were glued to the tension face of the beams. Four specimens were tested having different thickness of the CFRP layer. The design of the beams was such as to compare the results with the tests carried out by M'Bazaa I., Missihoun M., Labossiere P. (ref. XX-1). The results indicate that geopolymer provides excellent adhesion both to concrete surface and interlaminar planes of fabrics. All the specimens failed by tearing of fabrics. Geopolymer adhesive is fire-resistant (up to 1000°C), does not degrade under UV light and is chemically compatible with concrete. This inorganic polymer is a water-based alumino-silicate. Its performance is better than organic polymers. It does not require any special protective equipment other than gloves. The stiffness of the beams increased with the number of CFRP layers as expected. The beams strengthened with CFRP exhibited more dense crack pattern with smaller widths as compared with control beam.

4.3.6. OH - Ohio Department of Transportation, Wright Patterson Air Force Base

Reference: [OH-2]

A series of bending test was carried at Wright-Patterson AFB to study carbon fiber plates glued to bottom of beams as reinforcement. A commercial graphite/epoxy system (AS4C/1919 from Hercules Inc.) was used. Plates having both unidirectional and two directional lay-ups of the fibres were applied to beams. Forty specimens were tested. Four configurations (types) of composite plates were chosen:

A - single plate w/o lap joints,
B - single lap joint in maximum moment region,
C - two single lap joints outside of maximum moment region,
D - two coupler in locations as in conf.C.

The adhesive surfaces were prepared prior to application of reinforcement. Vacuum Bag was used to provide good interfacial bond of the plates to beam surface. The failure of lap joints in configuration B proved its inadequacy. Configuration D introduces smaller stress concentrations in comparison to type C lap joint. No failures were noted in type D joint and it was selected for use in planned field demonstration. The results of the tests indicated the substantial increase of beam stiffness and strength. Good agreement was achieved in comparing the test results with the theoretical predictions. The results of the experiment were aimed at gaining experience before the field demonstration on a bridge in Butler County in Ohio.

4.3.7. WVU - West Virginia University, Constructed Facilities Center

Reference: [WVU-1]

Twenty one reinforced concrete beams were tested using CFRP and steel plate strengthening systems. The beams were preloaded up to cracking of concrete and close to yielding of steel Reinforcement prior to application of strengthening system. The four-point bending setup was selected with 9-foot span and 3x3-foot force distance. The test setup was instrumented to measure the strains and deflections. The load was applied monotonically at constant rate. The use of CFRP increased the load carrying capacity of the beams. The average strength increase equals 57%. Steel plate strengthening has not resulted in any significant increase (6%). The effect of wrapping configuration is not evident between different groups of wrapped beams. The beams strengthened with CFRP failed by crushing of concrete between the points of load application, without any delamination of carbon-fiber wrap. High strength to weight ratio of CFRP resulted in a better physical integration and performance.

4.3.8. EMPA - Switzerland: Swiss Federal Laboratories for Materials Testing and Research

Reference: [SOA-1]

Meier (1987) reported the use of thin CFRP sheets as flexural strengthening reinforcement of concrete beams. He showed that CFRP can replace steel with overall cost savings in the order of 25 %. Kaiser (1989) load tested CFRP composites on full scale reinforced concrete beams and showed the validity of the strain compatibility method in the analysis of cross sections. It was suggested that inclined cracking may lead to premature failure by peeling-off of the strengthening sheet (BF type of failure). The study included the development of an analytical model for composite plate anchoring, which was shown to be in agreement with tests results.

Reference: [EMPA-1]

Table 2.4 from 2.1.4, [EMPA-1], list criteria which specifically relate to the use of composite material as a post-strengthening material for structures and applies particularly to prestressed laminates. From this table, it is clear that Carbon Fiber Reinforced polymer Composites most closely fulfill requirements for the post strengthening of structures.

Considering the case when the plate is not prestressed before bonded, the modulus of elasticity of the plate material is of great significance, because only stiff plates are able to relieve the stresses in the existing internal steel reinforcement. Therefore, CFRP has a noticeable advantage over GFRP.

The experimental work showed that the possible occurrence of shear cracks may lead to peeling off of the strengthening composite. Thus, shear crack development represents a design criterion. The following failure modes were observed in the flexural loading tests:

Failure of concrete compressive zone when the maximum concrete compressive stress is reached.(Failure type CC).

The CFRP composite failed suddenly with a sharp explosive snap; the impeding failure was preceded well in advance of the failure by cracking sounds.

Vertical shear failure of concrete (Shearing of the concrete in the tensile zone, failure type CS)

Fatigue failure of reinforcing bars (Failure type RF).

Inter-laminar failure of the laminate.

Interlaminar shear within the CFRP laminate (Failure type FD)

Adhesion failure FRP-concrete surface (Failure type BF)

4.3.9. XX - Other Research Institutions

Reference: [XX-1]

At the Universite de Sherbrooke (Canada) the experimental program was carried out to investigate the flexural strength of reinforced concrete beams post-strengthened with CFRP. The unidirectional fabrics were glued to the tension face of the beams. Total of eight beams were tested. One of the test beams (PC) was not strengthened with CFRP and it served as the control specimen. The Tonen Forca Tow Sheet composite was applied to bottom of the beams. The deflections of the beams were monitored using LVDTs in mid-span. The load was applied monotonically up to failure. The crack pattern in the beams post-strengthened with CFRP was more dense and uniform with smaller widths in comparison to control beam. Final load occurred under the load at least 56.4 % larger than the control beam. In all cases the beams failed due to sudden delamination of composite (peeling-off failure). Also the stiffness of the CFRP beams increased substantially what resulted in the lower deflections at failure. The placement of CFRP at different small angles had no particular influence on strength and stiffness. The analytical models used in the work provided the reasonable approximation of the flexural behavior.

References: [XX-2] [XX-4]

At the US Navy Facilities Engineering Service Center the experimental program was carried out to investigate the flexural strength of under-reinforced concrete beams strengthened with CFRP. The unidirectional Tonen FTS-C1-20 fabrics were glued to the tension face and the sides of the beams in different way. Total of six simply supported beams were tested. The load was monotonically increased up to failure. The tests were instrumented with strain gages and LVDTs. The experimental results were compared with the anaytical computations. The results of the study indicate that the flexural strength can be significantly increased by bottom CFRP but the beams will fail in shear. Additional vertical tows at beams sides can provide sufficient shear strength and revert the mode of failure to bending. Up to 90% increase of bending strength was achieved.

References: [XX-5] [XX-6]

At King Fahd University of Petroleum and Minerals the experimental program was carried out to investigate the flexural strength of reinforced concrete beams strengthened with CFRP. Total of ten simply supported beams were tested. Prior to application of FRP the beams were preloaded up to approx. 85% of their ultimate capacity to introduce initial damage. The fiber glass plastic FRP with three layers was glued to the tension face of the beams. Four different configuration of strengthening were chosen:

A. Plates bonded to beam soffit;
B. Conf. A + anchorage with steel bolts;
C. Conf. B + side FRP plates;

D. Jacket plates bonded to soffit and sides of beams.

The rehabilitated beams were tested up to failure. The conclusion from the tests were as follows:

1. The shear and normal stresses at the plate curtailment increase with increasing FRP plate thickness, leading to premature failure by plate separation and concrete rip-off.
2. Steel anchored bolts eliminated plate separation and the curtailment zone for large-thickness plates. The repaired beams failed due to diagonal tension cracks.
3. Jacket FRP plates provided the best anchorage system to eliminate plate separation and diagonal tension failure, and develop the flexural strength of the repaired beams.
4. Repaired beams provided enough ductility despite the brittleness of FRP plates, indicating effectiveness of FRP for external strengthening.

Reference: [XX-37]

Experimental program was conducted at Leheigh University (Pennsylvania) in order to test the flexural behavior of concrete beams strengthened with different glued-on systems. A series of 16 under-reinforced beams was tested. Two beams without strengthening served as control samples. The following different plates were used for the remaining beams:

1. A molded fiberglass standard pultruded fiberglass sheet;
2. 0/90 deg molded fiber reinforced plastic;
3. A molded fiberglass standard pultruded fiberglass channel;
4. 0/90 deg 65% GFRP / 35% CFRP;
5. A spring-orientation Glass FRP;
6. 0/60 deg Carbon FRP;
7. 0/90 deg Carbon FRP;
8. Unidirectional Aramid FRP;
9. Mild steel plate.

A standard ready-mix concrete was used. Before the application of FRP the adhesive surfaces were prepared by sandblasting and high pressure water washing.
Different anchorage systems were used:

- FRP extended up to support;
- Partial height bonded angles;
- Full height bonded plates connected by bonded angles.

The experiment proved the increase of strength and stiffens of beams with FRP from 19 to 99% over control samples. All FRP plates demonstrated brittle behavior. The role of anchorage type was confirmed by the test results.
A computer model was developed which allowed for satisfactorily accurate prediction of the beams flexural strength. To fully validate the model more tests are necessary.

4.4. Shear Behavior

Shear performance of the FRP strengthening systems is a major research concern due to the following factors:

- Multidimensional state of strength, requiring the use of multidirectional FRP composite laminates.
- Limited development lengths of the FRP laminate may require additional anchorage provisions (e.g. bolted connections).
- Limitations of access to the sides of the girders (e.g. box girders in a slab bridge)

The available information confirms that FRPs can be successfully used for increasing the shear capacity of concrete elements provided anchorage issues are properly resolved. The following sections summarize the experimental investigation dealing with the shear behavior of FRP strengthened concrete elements. The information covered is classified according to its source.

4.4.1. SOA - State of the Art Reports & Review Documents

Reference: [SOA-1]

External shear reinforcement in the form of bonded FRP overwrap has been applied to beams with insufficient shear strength. Tests conducted by Rider, 1993, have indicated that this procedure provided sufficient shear resistance to allow full development of the flexural capacity of the beam.

4.4.2. DE - University of Delaware, Delaware Department of Transportation

Reference: [DE-5]

The paper presents the comparison of effectiveness of a variety of woven composite fabrics with different strengths and stiffness (Aramid, Glass and Graphite FRP) in application to shear strengthening. Also included is the study of the orientation of bonded fabric on its shear performance. The tests were carried out on a total of twelve T-beams designed according to ACI specifications. The beams were underdesigned in shear compared to their flexural capacity. Woven composite fabrics with fibers oriented at both 0 and 90 deg, with equal distribution in each direction were employed. The following fabrics were used:

- Plain-weave Aramid fabric;
- Crowfoot satin weave E-glass fabric;
- Plain-weave Graphite fabric.

The beam surface was prepared prior to bonding FRP. It was mechanically abraded until the layer of laitance was removed, followed by air-blasting to remove any loose particles. In application of FRP the vacuum bag was used in order to remove the excess of adhesive and obtain best possible bond. Four-point bending setup was used. Three control beams had no FRP reinforcement for comparison. All tested beams failed in shear, with strengthened beams having significantly higher ultimate load. All beam experienced brittle failure mode with significant tension cracking in constant shear span. Wrapping with FRP increased the carrying capacity by 60-150% over control beams. The order of beam capacity was as follows: Control, Aramid (82.7% increase), E-glass (87.9% increase), Graphite (91.1% increase). The beams wrapped with Graphite with 45/135-deg orientation displayed a 125.3% increase in strength. The theoretically computed shear strengths for control beams were, on average, 28% lower than the measured values. An analytical procedure was developed to take into account the share of FRP. The shear capacity could be estimated with 9.1-13.2% accuracy. The predictions for beams with FRP proved more accurate than for the control beams. All predicted nominal shear capacities are conservative.

4.4.3. XX - Other Research Institutions

Reference: [XX-32]

Tests were carried out on three reinforced concrete beams to investigate the effect of FRP wrapping of the RC beams having the floor slab. Two of the beams had rectangular cross-section, one of them strengthened with FRP, and served as control beams. Third beam with T-shaped cross section was strengthened with FRP by anchoring the sheet at its ends into the underside of the flanges. Tonen Forca Tow sheet was used having the orientation perpendicular to beam axis. The Anti-symmetric Moment method was selected as the test setup. Comparable force-deflection diagrams and ultimate forces for both FRP-strengthened beams proved, that such methods of strengthening can be effectively used for beams with floor slabs. A method of analytical prediction of shear capacity using the so called "converted shear reinforcing bar ratio" was discussed.

Reference: [XX-33]

At University of Manitoba tests were carried out on four I-shaped beams of AASHTO design to investigate the shear characteristics of FRP reinforcements. The purpose of the tests was to collect the data necessary to strengthen the twin five-span continuous precast pretensioned concrete bridge. In the experiment, the model scale of 1:3.5 was assumed in regards to all applicable dimensions. Three types of CFRP were used in six different configurations. First beam served as control specimen. The beams were designed to carry the same shear stress as the ones in the structure. The beams were tested at each end in order to determine the most effective strengthening scheme. The following FRP strengthening systems were chosen:

- Beam No.2 - Forca Tow Sheet - Tonen Corporation,
- Beam No.3 - Replark - Mitsubishi,
- Beam No.4 - Tyfo™ S Fibrwrap™ - Hexcel Fyfe Company.

The following surface preparation techniques were used:

- Beam No.2 - Grinder, wire brushing, high pressure air;
- Beam No.3 - High pressure water blasting;
- Beam No.4 - High pressure water blasting;

The configuration of FRP wrapping was as follows:

- Beam No.2 - 1st end - vertical wrapping, 2nd end - vertical + horizontal wrapping;
- Beam No.3 - 1st end - 45 deg wrapping, 2nd end - 45 deg + vertical wrapping;
- Beam No.4 - 1st end - 45 deg wrapping, 2nd end - 45 deg + horizontal wrapping;

The non-symmetric test setup was used which allowed to test the ends of each beam in independent run. The strains were monitored using data acquisition system.
The results of the tests proved that the presence of FRP reinforcement improved the ultimate shear capacity of the beam in the following amount as compared to control beam:

- vertical wrap - 10% widely spaced sheets, 17% closely spaced sheets;
- horizontal + vertical wrap - 34%
- diagonal 45 deg wrap - 26%
- diagonal 45 deg + vertical wrap - data N/A
- diagonal 45 deg + vertical wrap - data N/A

It was concluded that the effectiveness of FRP overall effectiveness of diagonal wrapping for shear is higher than the horizontal/vertical combination.

Reference: [XX-31]

The investigation was done in order to evaluate the effect of shear strengthening of precast reinforced concrete bridge girders using CFRP sheets. Three hat-shaped beams salvaged from a demolished bridge were used. Uni-directional CFRP sheets were bonded to vertical faces in various arrangements. The sheets were applied continuously throughout the shear span. Either one or two layers of CFRP were bonded to the webs. One layer was oriented vertically. The second, if used was oriented horizontally. The members were tested up to failure. Four-point bending setup was chosen. Both strains and deflections were monitored throughout the testing. All the beams were tested twice, with the ends which failed first repaired before second run. Shear failure was governed by the strength of concrete rather than the CFRP material. The experiments indicated that anchorage is a key consideration. All the failure modes were by diagonal tension cracking. The effect of the CFRP was noticed once the cracks began to open up, at which time the sheets began to influence the behavior of the member. In general bond between CFRP and concrete was generally excellent. Some debonding took place in areas where the concrete surface was uneven. The horizontal CFRP sheets did not have significant influence on shear capacity. The results showed the increase in shear capacity of between 21% and 55% in comparison to unreinforced control beam. CFRP provides the crack control when glued to the surface of concrete members. The most efficient is the orientation perpendicular to crack line. If cracks are pre-existing, CFRP sheets may easily be applied in the optimum orientation. One of the possible analytical method of taking the CFRP strengthening into account is by using the truss model analogy, where CFRP sheets are treated the same way as stirrups. The truss model analogy was successfully modified to predict the strengthening effect of CFRP sheets. The use of this analytical procedure needs further verification for other types of sections and strengthening layouts.

Reference: [XX-43]

The experimental program was carried out at King Fahd University of Petroleum and Minerals to investigate the shear capacity of concrete beams strengthened with Fiberglass Plate Bonding. The beams were designed to have the shear deficiency in shear capacity; thus shear failure was the dominant mode of failure. Sixteen RC beams were tested The beams were divided into four main groups according to the FGPB shear repair scheme:

- Group C - control beams having no shear repair;
- Group S - beams repaired by shear strips;
- Group W - beams repaired by shear wings;
- Group J - beams repaired by U-jackets.

Each of the groups was subdivided into two subgroups:

- Subgroup O - beams having no flexural repair;
- Subgroup P - beams repaired in flexure by bonding a 3-mm thick flexural plate to the soffit of the beam to upgrade its flexural strength.

Prior to repair the beams were damaged to a predetermined level defined subsequent to testing of the control beams, which were unrepaired. Four-point bending setup was used. The tests were monitored with strain gauges and LVDTs. The tests revealed that the shear capacity is almost identical for both strips (Group S) and wings (Group W). Shear repair by jacket (Group J) is better than by strips or wings, thanks to good anchorage at the bottom of the beam, which prevents premature peeling failure. Thanks to it the beams with jackets failed in flexure. beams from groups S and W failed in shear. All of the repair methods restored the stiffness of the beams degraded during the preloading stage.

4.4.4. EMPA - Swiss Federal Laboratories for Materials Testing and Research

Reference: [EMPA-1]

A new method, which allowed the effective strengthening of the areas where the shearing force is present, was developed and tried out in several tests. (see figure 5 EMPA-1) The inner stirrup reinforcement is supplemented by a stressed or limply applied external strengthening component manufactured from advanced composite materials; this can be braided or unidirectional in form. The prestressing material is wrapped around the cross-section on one side and is anchored in the compression zone on the opposite side.
The shearing effect is influenced by many parameters and it can therefore be predicted only approximately. A vertical offset on the concrete surface can lead to bending forces

in the laminate which can exceed the concrete strength limits. Local unevenness can result in the shearing effect even at small loads, particularly in the case of thin, initially unstressed composites. Therefore CFRP should have a minimum thickness equal to 1 mm.

When a crack opens a vertical offset can occur. The shearing effect of a CFRP composite due to a vertical offset is dependent on the following parameters: loading (moment, axial force and shear force), geometry (Concrete, steel reinforcement., CFRP composite), mechanical properties (concrete, CFRP composite, rebars), geometry of the crack (micro and macro roughness, crack width, offset in the vertical direction) and the maximum elongation of the composite due to external forces.

The loading capacity of systems strengthened with initially unstressed laminates may be reduced if shearing is responsible for the failure.

4.5. Fatigue Properties

The fatigue properties of the FRP strengthening system are dictated by the characteristics of the fibers, type of matrix as well as the adhesives. Experimental results [EMPA 1, EMPA 11] showed that Carbon Fiber present an outstanding fatigue performance compared with Glass and Aramid. Therefore, CFRP sheets are particularly suitable for fatigue load conditions.

The following passages summarize the experimental works focused on the fatigue behavior of FRP strengthened concrete elements The information covered is classified according to its source.

4.5.1. FTS - Tonen Corp., H.S. Kliger & Associates, Structural Preservation Systems

Reference: [FTS-2]

The fatigue tests were performed on two bridge slabs taken from real structure after 26 years of service. One slab was strengthened with CFRP (Forca Tow Sheet FTS-C1-50) with two perpendicular layers. The strengthening was applied after performing $0.5x10^5$ of initial cycling. A decrease in deflections of the strengthened slab by 20% was observed in the following series of cycling. Non-strengthened slab failed after $1.2x10^5$ cycles of 15 ton load. The strengthened slab survived over $5x10^5$ cycles of load without any breakage of carbon fiber sheet and no peeling-off. From the results of the tests it was concluded that CFRP is a very effective way to increase the fatigue endurance.

4.5.2. OH - Ohio Department of Transportation, Wright Patterson Air Force Base

Reference: [OH-3]

Tests were carried out on RC beams with external CFRP reinforcement. A commercial graphite/epoxy system (AS4C/1919 from Hercules Inc.) was used in the form of 3-ply prepreg. Fatigue damage was measured using two non-destructive methods: pulse velocity and natural frequency. Non-reversed fatigue load of sine wave form was applied up to 2 million cycles. Four control tests were tested statically for comparison. Beams which did not failed due to fatigue were tested statically to failure. The static flexural strength of control and fatigued beams were approximately the same. The endurance limit of beams reinforced with CFRP was greater than 250% of static flexural strength, which proved excellent fatigue properties of CFRP strengthening.

4.5.3. DE - University of Delaware, Delaware Department of Transportation

Reference: [DE-2]

Chajes tested 15 block specimens to evaluate their fatigue resistance of the composite material-concrete interfaces. The results indicated that fatigue resistance of the bond is a function of both the stress range and the maximum level of stress. Four of the five specimens cycled at a stress range of 25 % of the bond strength reached 2 million cycles without failing, and the unbroken specimens proved to be undamaged when tested statically. The three specimens cycled at a 45 % stress range and having a maximum stress of 55 % of ultimate reached, on average, 1.2 million cycles. The two specimen cycled at a 45 % stress range and having a maximum stress of 75 % reached, on average, only 187,000 cycles.

4.5.4. SOA - State of the Art Reports & Review Documents

Reference: [SOA-1]

The time -dependent behavior of concrete beams strengthened with FRP plates was studied by Kaiser (1989), Duering (1993), and Plevris and Triantafillou (1993). In a series of tests, failure under fatigue loading was always initiated by rupture of the tensile reinforcing bars. This resulted in transfer of stresses from the reinforcing bars to the CFRP, which eventually failed as well. Hence, the flexural capacity of the members was controlled by the strength of steel under repeated failure. Creep experiments were performed to determine the effect of CFRP on the behavior of the strengthened beams. It was concluded that the composite sheet can be modeled as a creep-free element perfectly bonded to the concrete.

Where the loading was repeated for 10 million cycles, carbon-epoxy composites have better fatigue strength than steel, while the fatigue strength of glass composites is lower than steel at a low stress ratio. (Schwarz 1992)

4.5.5. EMPA - Swiss Federal Laboratories for Materials Testing and Research

Reference: [EMPA-11] [EMPA-1]

CFRP laminates exhibit excellent fatigue behavior. Through the bonding of the CFRP laminates the inner reinforcement is relieved. Tests with very high vibration amplitudes yielded excellent results over more than 10 million load cycles.

Deuring performed fatigue tests on a strengthened beam with CFRP laminate with a span of 6m under realistic loading ranging from 125.8 kN to 283.4 kN, which is corresponding to 131 MPa-262 MPa for the rebars and 102 MPa-210 MPa for the laminate. After 10.7 million cycles the tests were continued in an environmental condition where the temperature and relative humidity are 40° C and 95 %, respectively. After a total of 12 million cycles the first steel reinforcement failed due to fretting fatigue. The joint between the CFRP laminate and the concrete did not present any severe strain fatigue. After 14.09 million cycles the second reinforcing bar failed due to fretting fatigue. After the failure of the third reinforcing rod, the CFRP laminate was sheared from the concrete.

Kaiser investigated a 2 m span beam strengthened with CFRP laminate under exaggerated fatigue loading ranging from 1 kN to 19 kN., which is corresponding to 12 MPa-407 MPa for the rebars and 11 MPa-205 MPa for the laminate. After 480,000 the first fatigue failure occurred in one of the two reinforcing rods in the tension zone; after 560,000 cycles the second reinforcing rod failed; after 750,000 cycles the first damage to the composite appeared in the form of fracture of individual rovings of the laminate; after 805,000 cycles the composite finally failed.

4.5.6. FTS - Tonen Corp., H.S. Kliger & Associates, Structural Preservation Systems

Reference: [FTS-6]

The 26 years old bridge slab strengthened with CFRP sheet was subjected to $0.5*10^5$ cycles under a 10 ton load level and $5*10^5$ cycles under a 15 ton load level. The strengthened slab did not break down after the test, while the unstrengthened slab did break down at $1.2*10^5$ cycles under the 15 ton load level.

4.5.7. XX - Other Research Institutions

Reference: [XX-26]

Under tension-tension fatigue load cycling between 10 % and 30 % of the tensile strength, both CFRP grid can endure 4 million cycles. After enduring 4 million cycles, the grid retained 93 % of its original tensile strength.

Reference: [XX-28]

Fatigue strength of CFRP rods was higher than that of GFRP and AFRP rods and the CFRP rods held more than 4 million fatigue cycles in the case that the maximum stress was less than 87.5 % of the mean tensile strength independent of the amplitude (Uomato, RILEM 95). This confirms the fact that Carbon fiber composites exhibit an excellent fatigue resistance.

4.6. Bond Properties

The interface bond between the FRP laminate and the concrete surface is one of the critical factors controlling the performance of the FRP plates strengthening systems. A number of studies investigating the flexural or shear behavior, incorporated also the issue of bond as a factor controlling the failure mode of the strengthened element.

In the following sections experimental studies aimed at investigating bond are reviewed.

4.6.1. FTS - Tonen Corp., H.S. Kliger & Associates, Structural Preservation Systems

Reference: [FTS-5]

Tests were performed using the axially loaded prism-shaped specimens to investigate the bonding strength of CFRP. Both high tensile (HT) and high modulus (HM) carbon fiber sheets were used. A total of 9 specimens was tested. The adhesive surface was prepared using the water jet and sander. In most samples the failure took place in the interface layer of concrete. Surface treated by water jet showed two times higher bonding strength than surface prepared by ordinary sander. The bonding strength increased also when the number of lamination layers was higher.

4.7. Analytical Models

Successfully use of FRP strengthening systems require development of proper analytical models. Existing models focus on flexural and shear capacity of concrete elements, particularly beam sections. The majority of models are based on the theory of compatibility of deformations and equilibrium of forces. One of the issues is the selection of the appropriate sequence of failures of the constituent materials. Brittle failure modes of the FRP materials should be avoided.

The following passages summarize the analytical models of FRP strengthening systems. The information covered is classified according to its source.

4.7.1. AZ -University of Arizona

Reference: [AZ-4]

Saadatmanesh, H and Ehsani, M.R presented analytical models based on the compatibility of deformations and equilibrium of forces to predict the stresses and deformations in concrete beams strengthened with Glass Fiber Reinforced Plastic (GFRP) plates epoxy-bonded to the tension face of the beams. It also investigate the effects of design variables such as steel reinforcement ratio, concrete compressive strength, plate area, and plate stiffness on the yield and ultimate moments of upgraded beams. Equations for calculations of strains and stresses in the FRP plate, steel rebar, and concrete, as well as the curvature at midspan, are calculated using an incremental deformation technique. Based on this study, it was found that the analytical models based on the compatibility of deformations and equilibrium of forces presented reasonably approximate the behavior of concrete beams externally reinforced with epoxy-bonded fiber composite plates, when a tough epoxy is used. Bonding a composite plate to a concrete beam can increase the stiffness, yield moment and flexural strength of the beam. It also reduces the curvature at failure. This method of strengthening is particularly effective for beams with a relatively low steel reinforcement ratio. Increase of the compressive strength of the concrete do not appreciably increase the ultimate moment of the section. Failure can be reach as a result of rupture of the plate, crushing of concrete in compression, or failure of the concrete layer between the plate and the reinforcing bars.

4.7.2. WVU - West Virginia University, Constructed Facilities Center

Reference: [WVU-1]

In the paper, the moment capacity increase due to longitudinal carbon tow sheet wrapping is discussed in terms of analytical modeling. The discussion is limited to failure modes after tension steel yielding of the wrapped concrete beam. Once the steel reinforcement yields, either the concrete can fail in compression or CFRP sheet can rupture due to tension. Other modes such as debonding, effect of creep, slip and aging of materials are not considered in the paper. The linear stress-strain curve was assumed for CFRP unidirectional sheet up to failure. The balanced, compressive and tensile types of failure are discussed and compared, depending on the section design. The analytical formulas describing each failure case are presented. The design procedure and flowchart are developed for the beam strengthened. The examples of design for different failure modes of beams wrapped with CFRP (Tonen Forca Tow) are included.

4.7.3. XX - Other Research Institutions

Reference: [XX-8]

The paper presents a numerical model for estimating the forces, moments, stresses, strains and deflections for any load level, of normal, damaged or repaired reinforced concrete beams. The model incorporates the stress-strain relationships for constituent materials. Creep and shrinkage can be also taken into account. The model was tested on a number of experimental data and proved its adequacy. Different material and geometrical properties can be applied in the computations.

Reference: [XX-19]

The paper presents the study of a balanced RC section strengthened with CFRP. Balanced conditions of RC section without and with FRP reinforcement are compared. The issues of Ductility and deformability are addressed. The recommendations for the design procedures are given.

Reference: [XX-20]

The reliability study of concrete structures in flexure having external FRP reinforcement is presented. The first part of the study concentrates on statistical character of design variables (geometrical and material properties) and their effect on material properties. The second part presents the methodology to establish the strength reduction factors for the given probability of failure. Third part evaluates the effect of each design variable on the reliability of the system.

Reference: [XX-38]

The paper presents the theoretical models for concrete beams prestressed with glued on FRP sheets. The models allow to estimate the maximum achievable prestress level so that the system will not fail near anchorage zones. Account is taken for the failure of either the adhesive layer or the beam material, depending on which of the two possesses lower shear strength. It is concluded that the method efficiency can be improved by increasing

the thickness of adhesive layer. The maximum achievable prestress level increases as both the adhesive thickness and the composite sheet cross section area fraction increase.
For FRP prestressed concrete beams additional anchoring mechanical devices may be necessary.
The presented model is valid for short-term behavior of FRP reinforced elements. The long-term viscoelastic behavior (creep and relaxation) has to be investigated,

4.7.4. SOA - State of the Art Reports & Review Documents

Reference: [SOA-1]

Ritchie (1991) tested a series of concrete beams strengthened with GFRP, CFRP, and AFRP and developed an analytical method based on strain compatibility to predict the strength and stiffness of the plated beams.

Triantafillou and Plevris (1990,1992) used the strain compatibility method and an analytical model for the FRP peeling -off mechanism based on the shearing dowel actions of both the steel reinforcement and the FRP plate to study the short-term flexural behavior of reinforced concrete beams strengthened with FRP laminates. The analytical results of failure mechanisms and corresponding loads were validated through a series of experiments employing thin CFRP sheets.

Plevris and Triantafillou (1993) developed an analytical model for predict the creep and shrinkage behavior of concrete beams strengthened with various types of FRP plates. It was concluded that:

- CFRP and GFRP affect the long-term response of strengthened elements.
- Increasing the area of these materials decreases the creep strains without affecting the time-dependent curvature, the tensile steel reinforcement stress, and the stress in the composite material.
- Increasing the area of FRP in general, tends to restrain the reduction of stress in the concrete compressive zone.

Plevris (1993) analyzed the flexure behavior of concrete beams strengthened with CFRP sheets. The concrete strength, CFRP failure strain, and CFRP area fraction were found to be the most influential on the variability of member strength. A reliability-based design procedure was also developed: Two strength reduction factors were derived to achieve a reliability index of about three over a broad spectrum of design conditions. It was concluded that the concrete, steel and ratio of live to dead load all have important effects on the reliability against flexural failure.

4.8. Durability

Civil Engineering structures are permanently exposed to aggressive agents. The use of FRP composite materials sheets has the advantage of corrosion resistance as compared to the use of steel plates. Other factors such as freeze-thaw conditions, fire resistance, ultraviolet radiation, chemical aggression and low temperatures require further investigation.

This new technology lacks long term infield experience about durability performance of the FRP sheets. Therefore experimental tests of these factors are needed.

The following sections summarize the experimental studies of durability of FRP strengthened concrete elements. The information covered is classified according to the durability factor tested and its source.

4.8.1. CA-CALTRANS California Department of Transportation

References: [CA-7,8,9,10]

Several composite overwrap systems have been proposed to the State of California, Department of Transportation (Caltrans) as alternative column casings for seismic retrofit. Caltrans prepared the document, "Prequalification Requirements for Alternative Column Casings for Seismic Retrofit", to provide a detailed listing of the requirements for prequalification of materials and process for composite column casing. These requirements include durability testing to demonstrate the ability of the proposed composite material systems to withstand a variety of climatic and unnatural exposure conditions. Environmental exposure include: 100% humidity, salt water, diesel fuel, cyclic ultraviolet light/water condensation, alkali solution, elevated temperature (140 F), and cyclic freezing and thawing. All testing has been performed by The Aerospace Corporation for Caltrans.
Flat laminates of each candidate composite system was subjected to these environmental exposure for various times or numbers of cycles as shown in Table 4.2. A partial test results summary is given in Table 4.3

Table 4.2 Environmental Durability Test Matrix for Composite Laminates

Environmental durability test	Relevant specification	Test conditions	Test duration
Water resistance	ASTM D 2247 ASTM E 104	100% Humidity at 100±2_F	1000, 3000, & 10000 hours
Salt water resistance	ASTM D 1141 ASTM C 581	Immersion at 73±3_F	1000, 3000, & 10000 hours
Alkali resistance	ASTM C 581	Immersion in $Ca(OH)_2$ at pH=9.5 & 73±3_F	1000, 3000, & 10000 hours
Dry heat resistance	ASTM D 3045	140±5_F	1000 & 3000 hours
Fuel resistance	ASTM C 581	Immersion at 73±3_F	4 hours
Ultraviolet resistance	ASTM G 53	Cycle between UV at 140_F & condensate at 104_F	4 hours per condition, 100 cycles
Freeze-Thaw resistance	None	Cycle between 100% humidity at 100_F & freezer at 0 F	24 hours per condition, 20 cycles

Table 4.3 Environmental Durability Test Results after 3000 Hour Exposure

Environmental exposure	Normalized Young's modulus				Normalized tensile strength				Failure strain (%)				Normalized short beam shear strength			
	C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4
Control	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.65	1.50	1.40	1.50	1.00	1.00	1.00	1.00
Humidity	1.08	1.03	1.04	1.00	0.95	0.91	1.04	0.98	1.50	1.35	1.40	1.50	0.68	1.13	1.11	0.83
Salt	1.02	1.02	1.05	1.01	0.89	0.92	0.94	0.96	1.50	1.30	1.25	1.45	0.72	1.03	1.02	0.88
pH 9.5	0.99	1.03	0.99	1.00	0.95	1.03	0.93	0.97	1.60	1.50	1.35	1.50	0.72	1.17	1.06	0.83
140 F	0.97	1.01	1.00	0.98	1.04	1.06	0.99	0.97	1.75	1.50	1.35	1.50	1.18	1.12	1.11	1.01
Freeze/Thaw	1.00	1.07	1.04	1.01	0.92	1.05	0.99	0.94	1.55	1.45	1.35	1.45	0.77	1.12	0.94	0.88
Ultraviolet	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Diesel fuel	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Note: C1, C2, C3, and C4 are different carbon fiber composite systems.
C4 = Tonen Carbon sheet

4.9. Low Temperature

The difference in the thermal expansion coefficients of concrete and of CFRP sheet results in stresses at the interface with changing temperatures. Indeed concrete and CFRP have significantly different coefficients of thermal expansion, normally:

Thermal expansion coefficient of concrete: $10*10^{-6}/°C$
Thermal expansion coefficient of CFRP: $<1*10^{-6}/°C$

4.10. Freeze-Thaw

The rehabilitation technique of external reinforcement of concrete elements by the use of CFRP sheets can not be effectively utilized in cold regions without investigating the durability of this new material in low temperatures environments.

Table 4.4. summarizes the most important points extracted from the literature review of freeze-thaw durability of concrete elements strengthened by CFRP sheets.

Table 4.4 Test Parameters Found on Literature Review about Freeze-Thaw (F.T.) Test

Reference	No. specimens	No. cycles	Tests Procedures	Type of FRP	Variable	Comments
DE-2	60 beams 38.1x 28.6x330mm Reinf Ø =2.38mm Adhes. = Sikadur 32 Aggregate size = 3.175 mm	50, 100	Epoxy-concrete compatibility ASTM C884-87 Freeze-thaw (F.T.) ASTM C672-84 Flexural test (4 pts) after environmental cycling	Aramid, E-glass, Graphite (Carbon)	type of FRP: Aramid, E-glass, Graphite (Carbon)	■ Graphite has higher env. durability than Aramid and E-glass. ■ For CFRP 21% decrease in strength compared with 17% of unwrapped beams. ■ Wet/dry cycles more critical than Freeze-thaw test. ■ Change in failure mode due to environmental exposure. ■ Partial debonding prior to failure
DE-3	Field application Foulk Road bridge	(1 year)	6 beams	CFRP	- Performance during its first year. - Evaluation of bond characteristics. - Durability of joints	■ All of the single layer applications of CFRP were well bonded (5 beams) ■ 1 beam with 2 layers of the highest strength sheet was not well bonded. Assumed due to insufficient resin saturation during the bonding process.
XX-9	2 coupons 25.4 x 9.53 x 304.8 mm	300	Cut edges coated with epoxy 2%water solut. Temp = 0-40 F F.T. (ASTM C666) Flexure (ASTM D790)	Fiber glass composite	Edge coated-uncoated Salt water	■ Lost 20-30% flexural strength, rigidity and toughness ■ Loss due to only salt water exposure =5-10%
XX-25	FRP rods embedded in a concrete cube of 10 cm length	300	bond test CP110 ASTM and RILEM	GFRP, CFRP and Vynylon FRP bar	Bond strength	■ No great influence of the bond strength due to F. T. Cycles.

Reference	No. specimens	No. cycles	Tests Procedures	Type of FRP	Variable	Comments
XX-26	N.A.	N.A.	N.A.	CGFRP grid (74% glass, 26 % Carbon)	Range T	■ Increase ultimate tensile strength by 11% and 2.5% mod. Elasticity for a fall in Temp. of -30C ■ Decrease of 9.5% and 2.5% respect. for increase from room T to 50C.
XX-22	N.A.	N.A.	N.A.	N.A.	Combine env. Expos. Crack propagation	■ The freezer effect had little effect on crack propagation
CAN-1	42 columns, 15 were subjected to FT test 152 x 305 mm	200	Cycling = -18C to +20C	CFRP wrap	% of Reinf. # of CFRP layers Env. Conditions: F.T. test Low Temperature water	■ CFRP wrapped concrete columns exposed to F. T. cycling showed a significant increase in strength (3 times) compared to unwrapped columns exposed at the same cond. ■ A second layer of CFRP provides an increase of 15% in strength ■ The wrapped columns subjected to F.T. cycling failed in a more catastrophic manner than those at room Temperature.
CAN-2	18 beams	N.A.	40C one week, -23C one week for 2 months Flexural test (3pt. Bending)	N.A.	Accelerated env. Exposure	■ 7% Reduction in strength for beams subjected to this hot-cold cycles. ■ Results from hot-cold cycles are quite close to those of long term exposure. ■ The effect of Temperature is more important than humidity in term of reducing the bonding strength.
CAN-4	12 beams 102 x 152 x 1220 mm As = 4 # stirrups	50	F.T. cycle -18C to +20C (cold room overnight to water bath)	CFRP	- # of CFRP sheet (0,1) - Orientation of sheet (long vs. Transv.) - Freeze-thaw vs. Room Temperature	■ No decrease in ultimate strength due to F.T. cycles ■ Strengthening with CFRP improves strength and ductility. ■ No difference in failure mode when compared with control beams. ■ F.T. cycling affect cracking behavior but does not affect ultimate behavior

N.A. = Information not available

In the following sections experimental studies aimed at investigating freeze-thaw durability of concrete elements strengthened by CFRP sheets are reviewed.

4.10.1. DE - University of Delaware, Delaware Department of Transportation

Reference: [DE-2]

At the University of Delaware, tests were performed in order to investigate the environmental durability of the composite fiber materials: Aramid, E-glass and graphite (carbon) fibers. The environmental durability studies involved subjecting the 60 small scale beam specimens to aggressive environments (the beams were exposed to repeated wet/dry and freeze/thaw cycles while sitting in a solution of calcium chloride.) Exposure times were varied and the flexural capacity of the exposed beam were compared with those not exposed. Once the beams completed the environmental cycling they were loaded to failure in four point bending. The results of the test indicate that the beams reinforced with the graphite fabric have greater environmental durability than those with Aramid or E-glass. After being subjected to environmental conditions, only graphite reinforced beams maintained nearly all of their strength advantage over the unwrapped beams. Graphite fabric proved the most suitable in applications involving environmental aggression. While both the Aramid and E-glass reinforced beams showed a 36 % decrease in strength due to 100 wet/dry cycles, the graphite reinforced beams dropped in strength by only 19 % (as compared to 12 % drop in strength of the unstrengthened beams). For freeze-thaw test,100 cycles, a decrease of 21% on the beam strength was reported (compare with 17% of unwrapped.) Of the two conditions the wet/dry cycling led to greater degradation. The tests also revealed that the environmental exposure can lead to changed mode of failure compared to non-exposed specimens. Partial debonding was experienced prior to failure.

Reference: [DE-4]

By Finch et al., bond tests using single-lap shear test method are being conducted on specimens(25.4 mm-wide graphite/epoxy plate bonded to a concrete block) which has been (1) immersed in fresh and saline water, (2) exposed to winter weather, and (3) subjected to repeated wetting and drying cycles.

4.10.2. Other Research On Freeze-Thaw

Reference: [XX-9]

Cycles of freezing and thawing temperatures will probably magnify the effects of water absorption. The expansion of the freezing water causes further delamination and interfacial failure. Two commercially available fiber glass composite coupons were placed in a 2 % salt water solution and subjected to 300 cycles of freezing and thawing, with the temperature ranging -17.8° C (0° F) and 4.4° C (40° F). Results indicates significant loss(20-30 %) in flexural strength, rigidity, and toughness. For only salt water, the percentage reduction is 5-10 %.

Reference: [XX-25]

Glass, Vynylon and carbon FRP bar is not influenced to the bond strength so much by 300 cycles of freezing and thawing. Aramid FRP (braided and coiled types) reduce bond strength gradually with process of freezing and thawing (by 50 % at 600 cycles).

Reference: [XX-26]

The ultimate tensile strength of Carbon-Glass Fiber Reinforced Plastic (CGFRP) grid (74 % glass+26 % carbon) increases by 11 % and modulus of elasticity by 2.5 % when the temperature falls to -30° C. On the other hand, tensile strength and modulus of elasticity decrease by 9.5 % and 2.5 %, respectively, when the temperature rises to 50° C from the room temperature.

Reference: [X-22]

Bourban et al. studied the combined effects of stress and environmental exposure on the steel-composite joints with three epoxies using the wedge-crack extension test. The crack propagation was affected by hot water, salt water, room temperature water, and freezer-thaw in the order of important environmental effect. The freezer itself had little effect on crack propagation.

Reference: [XX-27]

Shulley et. al investigated the durability of five different types of reinforcing fibers(3 carbon and 2 glass) bonded on steel using the wedge-crack extension test. Different types of fibers had different durabilities against different environments. The crack growth was affected by hot water(65° C) , sea water, aqueous environment, and freeze-thaw (-18° C~20° C)in the order of important environmental effect. A sub-zero environment(-18° C) had little effect on crack growth (a slightly positive effects for some fibers).

Reference: [XX-29]

Based on results of a survey of 40 to 75 year old, non-entrained concrete dams, a new one-sided freezing test is proposed. In this survey, most of the deterioration was found in areas away from the direct exposure to water, but subject to many cycles of freezing in air. The unfrozen side is exposed to water and the freezing side is exposed to air, simulating a filed exposure

Reference: [XX-30]

Stresses developed in composites due to changes in Temperature and Relative Humidity are due largely to mis-matches in the different moisture and thermal coefficients of expansion of the materials. In this paper, a general model is developed directly related to the temperature and humidity related restrained response of materials. This information is useful in developing predicting numerical models for the behavior of composites structures.

4.10.3. EMPA - Swiss Federal Laboratories for Materials Testing and Research

Reference: [EMPA-10]

When a change of temperature takes place the difference in the coefficient of thermal expansion of concrete and the composites result in thermal stresses at the joints between the two components. After 100 frost cycles ranging from 20°C to -25°C, no negative influence on loading capacity of the three post-strengthened beams was found.

Reference: [EMPA-1]

Meier reported that when a change of temperature takes place, the differences in the coefficients of thermal expansion of concrete and the carbon fiber composites resulted in thermal stresses at the joints between the two components. After 100 frost cycles ranging from +20 °C to -25°C, no negative influence on the loading capacity of three post-strengthened beams tested was found.

4.10.4. CAN - Canadian Institutes and Universities

Reference: [CAN-01]

This paper presents the results of the performance in cold weather of circular concrete columns strengthened with CFRP wraps. 42 circular plain and reinforced concrete columns were tested. Test variables included percentage of reinforcement (0%. 1%, 2.3%) number of CFRP layers (0, 1, 2) and environmental exposure conditions(room Temperature, Freeze-thaw cycles -18 to 20C) and under water). 15 columns were submerged in water for 200 freeze/thaw cycles. After completion of the cold climate exposure, the columns were tested for axial strength and load versus axial strain plots were obtained. Based on the results of the experimental program, CFRP sheets proved to be feasible in strengthening columns in cold regions.

Reference: [CAN-2]

Beams of dimensions 51 x 76 x 279 mm, were externally reinforced with a Carbon/epoxy composite sheet and tested under flexure after being submitted to different environments. Unidirectional graphite/epoxy composite sheets were made by autoclave-vacuum molding using Newport NCT-301 composite prepeg. Thickness varies from 0.33 mm for 3 layers to 6 mm for 45 layers. Ciba-Geigy's structure epoxy adhesives AW106 and Rp1700-1 were used for the bonding procedure

Results showed that accelerated environmental exposure by water immersion for 60 days had slight positive effect on the load bearing capacity. Whereas hot-cold cycles for 60 days and long term outdoor exposure up to 28 months reduced the load bearing capacity for about 7%. The effect of temperature was more important than humidity. Hot-cold cycle is an effective method for accelerated test.

Reference: [CAN-3]

This paper reviews the existing information on the low temperature response of reinforced concrete members strengthened with FRP sheets. It reviews the material behavior of concrete, steel, and FRP at low temperatures, and discusses the observed behavior of reinforced concrete beams, with and without FRP strengthening when subjected to low temperatures.

Experiments on tensile loading of unidirectional FRP at low temperature (Dutta, 1990) have shown that the longitudinal strength of these composites drops at low temperatures. It is generally believed that, in unidirectional FRP with a high fiber volume fraction, tensile is primarily governed by the fiber properties.
To investigate the effect of freeze-thaw cycles, 6 test beams were subjected to 100 freeze/thaw cycles of 20C to -25C before being tested to failure in four point bending at room temperature (Kaiser, 1989). Half of these beams were cracked prior to adhesion of the laminate. During temperature cycling, the frozen beams were thawed by flooding the freezers with water at a temperature of approximately 20C. It was expected that water would enter into cracks and expand with subsequent freezing, resulting in peeling of the laminate. All frozen beams were brought to room temperature before being tested. A comparison of the breaking loads of the frozen beams with the breaking loads of the control beams showed no negative influence on the ultimate load capacity.
Concrete beams strengthened with FRP sheets may increase in strength when subjected to short-term exposure to low temperatures. Long-term exposure of such members must be investigated to determine the effects of creep and aging of the materials.

Reference: [CAN-4]

This paper presents the results of an investigation into the effects of Freeze- thaw cycling on the flexural and shear behavior of beams post-strengthened with CFRP sheets. 12 rectangular beams with different steel and CFRP reinforcement configuration were subjected half to 50 freeze-thaw cycles and half were kept in room temperature. All the beams were finally subject to 4 point flexural test. Researchers concluded that CFRP sheets are effective in strengthening flexural members exposed to freeze-thaw cycling. CFRP sheets can be used as external shear and/or flexural reinforcement. Strengthening concrete beams with CFRP sheets improve strength and ductility. Failure mode observed were:

- bond peeling of CFRP sheet (BF).
- rupture of CFRP fibers (FD)

No difference in failure mode between beams subjected to freeze-thaw and those at room Temperature. Freeze-thaw slightly affects cracking behavior of beams, but does not affect ultimate behavior. Finally, the theoretical predictions compare well with test results.

4.11. Chemical Aggression - Chloride and Salt Water

Excessive absorption of water in composites could result in loss of strength and stiffness. Water absorption produces changes in resin properties and could cause swelling, warping, and delamination in composites [SOA-1]. However, there are resins are formulated to be moisture-resistant and may be used when a structure is expected to be wet at all times.

The following sections summarize the experimental studies of durability of FRP strengthened concrete elements under weathering conditions and salt water effect.

4.11.1. MRK - Mitsubishi (Replark), Craig Ballinger & Associates

Reference: [MRK-3]

In weathering test of CFRP sheet, no reduction was observed in tensile and bond strength for 2000 hours of accelerated exposure period equals to about 7 years. The durability of the CFRP rod against salt water was checked in salt water for 1 year. No reduction of tensile strength was observed.

4.11.2. DE - University of Delaware, Delaware Department of Transportation

Reference: [DE-02]

Chajes et al. investigated the environmental durability of the composite fiber materials: Aramid, E-glass and graphite (carbon) fibers. The environmental durability studies involved subjecting the 60 small scale beam specimens to aggressive environments (the beams were exposed to repeated wet/dry and freeze/thaw cycles while sitting in a solution of calcium chloride.) The results indicate that the wet/dry cycling had a slightly more severe effect on the beams than did the freezing/thawing cycling. (Refer to section 4.10 Freeze-Thaw)

Reference: [DE-4]

By Finch et al., bond tests using single-lap shear test method are being conducted. (Refer to freezing and thawing).

4.11.3. XX - Other Research Institutions

Reference: [XX-9]

Two commercially available fiber glass composite coupons were exposed to 300 cycles of 2 % salt water. The percentage reduction in flexural strength is 3-7 %.

Reference: [XX-22]

Bourban and Shulley conducted their wedge-crack extension tests on the interface between steel and composites with different epoxies and different fibers, respectively. (Refer to freezing and thawing)

4.11.4. HF- HEXCEL FYFE Co.

Reference: [HF-1]

Fyfe et al. evaluated the durability of Tyfo™ S System(glass fiber) which is used to repair column. The test results show that salt water exposure did not effect the tensile strength of the panels.

4.11.5. FL - Florida DOT

Reference: [FL-1]

Sen et al. investigated the durability of S-2 glass/epoxy pretensioned beams subjected to cycles of wetting and drying with 15 % salt water solution to simulate tidal effects. The tests indicate a complete loss in the effectiveness of the fiberglass strands after 6 months for the precracked beams and 15 months for the uncracked beams.

4.12. Ultraviolet Light

Composites can be damaged by the ultraviolet rays present in sunlight. These rays cause chemical reactions in a polymer matrix, which can lead to degradation of properties. The problem can be solved with the introduction of appropriate additives to the resin[SOA-1.]

4.12.1. HF- HEXCEL FYFE Co.

Reference: [HF-1]

Fyfe studied weathermeter aging of Tyfo™ S System(glass fiber) exposed to ultraviolet and condensate. The test data show that the failure loads of the panels did not change significantly. He also studied thermal aging of the laminate. The results indicate that 140° F thermal aging had no negative effect.

4.13. Fire Resistance

Due to the different properties of the components of a laminate, the effect of temperature is more severe on the resin than on the fiber [SOA-1]. An adequate value of fire resistance of the FRP strengthened concrete elements is necessary to meet safety conditions provides by construction codes.

The following sections summarize the experimental studies of fire resistance of FRP strengthened concrete elements.

4.13.1. EMPA - Swiss Federal Laboratories for Materials Testing and Research

Reference: [EMPA-1][EMPA-10]

In 1994, by the EMPA, the 6 m beams strengthened with steel and CFRP sheets under 4 point loading were heated with a temperature of 925 k after 1 hour. After 8 minutes the steel plate came away from the beam strengthened with steel plate. During the test the fibers started to burn at the surface of the laminates of the 4 strengthened beams, thus causing a slow decreases in stiffness. The CFRP composites finally became unbonded from the beams after one hour. The main reason for the superior behavior of the CFRP composites compared with that of the steel plates was their low conductivity in the lateral direction.

4.13.2. MRK - Mitsubishi (Replark), Craig Ballinger & Associates

Reference: [MRK-3]

For CFRP sheet(with epoxy resin), the maximum fire resistant temperature is 260° C for 2 hours based on the fact that no strength reduction was observed after returning to ambient temperature.

4.13.3. XX - Other Research Institutions

Reference: [XX-23]

The tension test under heating for H8 (glass+carbon) grid shaped FRP, the heated strength decreases gradually from room temperature to 100° C, and remain about 60 % of the unheated tensile strength at around 100 to 250° C (20 minutes at 250° C). After cooling to room temperature, the heated strength return to its unheated tensile strength.

4.14. Field Applications

FRP strengthening systems have been used successfully in a number of field applications. Strengthening of flexural elements is among the most common usage, because the advantages of this new technique for the strengthening of flexural elements have been proved in numerous field applications in the United States and abroad.

The following sections summarize the field application of FRP strengthening systems in concrete structures. The information covered is classified according to its source.

4.14.1. FTS - Tonen Corp., H.S. Kliger & Associates, Structural Preservation Systems

Reference: [FTS-1]

A highway bridge having RC slab mounted on steel girders was strengthened with Forca Tow Sheet FTS-C1-30. The bridge after over 20 years of service exhibited many cracks in deck in both longitudinal and transverse directions. The fiber was applied as one longitudinal and one transverse layer with total area of 164 m^2. The application of strengthening took approximately two weeks. Traffic was not interrupted. The load tests were carried out prior and after the rehabilitation and the measurements readouts compared. The test were done at low (5 km/h) and normal (40 km/h) speeds of loading trucks. The deflections of the slab itself decreased by 15 to 20 percent. The strains of the main reinforcement were reduced by approximately 30 to 40 percent. Similarly, the strains in distribution bars decreased by approximately 20 to 40 percent.

References: [FTS-2] [FTS-3]

The CFRP Forca Tow Sheet was applied on Shirota bridge in Kyushu Province (Japan). Due to relaxing of the allowable loads (from 20 to 25 Tons) the stresses in main and distribution bars of the bridge slab exceeded the allowable limit of 1200 kg/cm^2 (17 ksi). The CFRP strengthening was designed to reduce the stresses below the allowable value. After the repair, the measurements were done using the strain gauges mounted at main and distribution bars. The measurements confirmed the substantial decrease of deflections and stresses by more than 30%. To confirm the long term reinforcing effect the strain gauges were monitored over a one year period. The results clearly indicate that the reinforcing effect is still effective after one year.

4.14.2. DE - University of Delaware, Delaware Department of Transportation

Reference: [DE-3]

The externally applied CFRP sheets were bonded to the beams of Foulk Road Bridge #26, Wilmington, Delaware. The superstructure consists of 24 simple-span adjacent box-beams, each 16.4 m long. The beam cross-section is 0.9m wide and 0.7mm deep, and has the wall thickness of approximately 130 mm. Six out of the 24 beams were retrofitted. The application was performed during a one-week period in October of 1994, taking a 5 men crew working 5-8 hours daily. The methods of monitoring the structure (both rehabilitated and unrehabilitated beams) relayed on periodic visual inspection, ongoing monitoring of ambient conditions, bond performance and crack growth. The initial inspection was performed immediately after application of CFRP. A sophisticated instrumentation was installed on the bridge to monitor ambient conditions. To date the Foulk Road Bridge rehabilitation performed well. No signs of deterioration was noticed in the applied composite. The unrehabilitated beams showed noticeable progress in cracking compared to rehabilitated ones.

4.14.3. Other Applications in North America

- Column wrapping projects, California: As a part of its general seismic upgrading program, the California Department of Transportation (Caltrans) placed confining jackets around bridge columns using fiberglass mat.
- Column wrapping projects, Reno, Nevada: In 1993, the Nevada Department of Transportation wrapped 96 0.3 m (3 ft) diameter columns with a proprietary FRP wrapping system.

- Strengthening of walls, Glendale, California: Fiber composite fabrics can be epoxy-bonded to the surfaces of masonry or concrete walls to increase the strength of these elements.
- Foulk Road bridge, Wilmington, Delaware: Carbon fiber Forca TM tow sheets were used on this 16.5 m (54 ft) long, simple span, prestressed, precast box beam structure that exhibited cracking indicative of the lack of transverse reinforcement. The bridge's superstructure was composed of 24 prestressed box beams placed adjacent to each other. For demonstration purposes, six of the beams were retrofitted. One ply of unidirectional CFRP sheet, with the fibers running transverse to the beam, was used on four beams. Two other beams used higher modulus, higher weight fabric, with on of those beams fitted with two plies rather than a single ply

4.14.4. Other Applications in Japan

- Wrapping projects: Forca Tow Sheet has been used extensively in Japan over 200 projects including tunnels, chimneys, side walls, and slabs.
- Carbon fiber sheet Replark ™ has been utilized as a strengthening system in Japan. Columns, road decks, bridge piers, bridge girders, retaining walls, slabs, floors and beams were repaired.

4.14.5. Other Applications in Europe

- Kattenbusch bridge (Meier 1987), an eleven-span post-tensioned concrete bridge consisting of two hollow box girders was strengthened with GFRP plates. The bridge was built with working joints at the points of contraflexure, where wide cracks appeared several years after construction. Additional reinforcement to control the crack width and to reduce the tendon stresses was provided by strengthening eight joints with steel plates and two joints with GFRP plates (30 mm thick, 150 mm wide, and 3200 mm long) per box girder. The plates were bonded to the top face of the bottom flange.
- Ibach bridge, Switzerland (Meier et al. 1992): Accidental damage to a prestressing tendon during maintenance work necessitated repair of this bridge in 1991. The bridge was strengthened with 5 m (16.5 ft) long CFRP laminates, two with a 150 by 1.75 mm (6 by 0.07 in.) cross sections and one with a 150 by 2.0 mm (6 by 0.08 in.) cross section, were applied to the bottom surface of the bridge. Approximately 14 lb. (6.2 kg) of CFRP were used in lieu of 385 lb. of steel.

CHAPTER 5
CONCLUSIONS

- Substantial amount of research done on FRP composites demonstrated the feasibility of the utilization of glued-on sheets as a strengthening technique for concrete structures.

- Carbon FRP composites seem, among different FRP laminates reviewed in this study, the most suitable for civil engineering applications. They possess excellent mechanical and durability properties.

- The best known CFRP systems currently used are produced by Tonen, Mitsubishi and Sika. Tonen and Mitsubishi products have similar characteristics. The Sika product differs in thickness and smaller choice of adhesives. Tonen *Forca Tow Sheet* is the most versatile product. The wide choice of different adhesives and primers makes it suitable for different conditions of applications.

- The simple application procedures developed, have made it possible to utilize CFRP sheets in field applications. However, the application of commercial FRP strengthening systems requires strict following of the specified procedures. So far, no standardized guidelines have been developed for this technique. Only by following the procedures recommended by each commercial product manufacturer the proper quality of strengthening can be achieved.

- The choice of the fiber strengthening system should in all cases be based on consideration of specifics of the application, such as:

  - purpose of strengthening;
  - the design of the structure or element;
  - conditions of application of FRP system (accessibility, temperature, humidity, degree of structural damage, surface preparation procedures etc.);
  - risks involved;
  - stress levels likely to occur in the retrofit system;
  - duration for which the repair/retrofit is being designed for.

- Durability issues should be addressed by a more intensive experimental program to ascertain the feasibility of this technique under particular environmental conditions.

- One of the key issues in successful application of CFRP composites is proper preparation of adhesive surfaces. The greater the level of damage (or contamination) of concrete cover, the more aggressive methods are necessary to remove the contaminated layer.

- A field test is recommended as the best way to corroborate findings performed in laboratory conditions.

- The high costs of the CFRP materials used in structural rehabilitation is fully compensated by the ease of application and low costs of workmanship.

- Not all issues have been fully explored. Further tests are necessary in order to identify the influence of different physical, mechanical and structural factors on performance of FRP laminates. In particular durability behavior of FRP composites requires further investigation.

CHAPTER 6
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FL - Florida DOT

FL-1. Sen, R., Mariscal, D., Shahawy, M., "Durability of Fiberglass Pretensioned Beams," ACI Structural Journal, ACI, Vol. 90, No. 5, Sept.-Oct., 1993, pp. 525-533.

MI - Michigan Department of Transportation

MI-1. MDOT 1996 Standard Specifications for Construction. Sections 701, 901,902 and 903.
MI-2. MTM113-97. Michigan Test Method for selection and preparation of coarse aggregate samples for freeze-thaw testing.
MI-3. MTM 114-97. Michigan test method for making concrete specimens for freeze-thaw testing of concrete coarse aggregate.
MI-4. MTM 115-97. Michigan test method for testing concrete for durability by rapid freezing in air and thawing in water.
MI-5. MDOT 1965 Standard Specifications for Road and Bridge construction. Division 5, Concrete Bridge Construction.

VHRC - Virginia highway Research Council

VHRC-1. Modification of ASTM C666 for testing resistance of concrete to freezing and thawing in sodium chloride solution. VHTRC- R16.Virginia Highway & Transportation Research Council. September 1978.
VHRC-2. Evaluation of Laboratory Equipment for Freezing and Thawing of Concrete. (Confidential and not for publication) January 1966.

TRRL - Transport and Road Laboratory. Dept. of the Environment. Dept. of Transport

TRRL-1. Macdonald M.D., "The flexural Behavior of Concrete Beams with Bonded External Reinforcement," Department of the Environment, Department of Transport, TRRL Supplementary Report 415.Crowthorne, 1978.

TRRL-2. Raithby K.D., "External Strengthening of Concrete Bridges with Bonded Steel Plates" Department of the Environment, Department of Transport, TRRL Supplementary Report 612.Crowthorne, 1980.

ASTM - American Standard Specifications

ASTM-1. ASTM C666-92. Standard Test method for Resistance of Concrete to Rapid Freezing and Thawing.

7.1. Glossary of Terms and Abbreviations

AFB	Air Force Base
DOT	Department of Transportation
FHWA	Federal Highway Administration
FTS	Forca Tow Sheet (Tonen Corporation)
MRK	Mitsubishi Replark
SCD	Sika (CarboDur)
FRP	Fiber Reinforced Plastic
GFRP	Glass FRP
CFRP	Carbon (graphite) FRP
AFRP	Aramid FRP

7.2. Contacts to Organizations Working on FRP

Table 7.1 Contacts To Organizations and Research Institutions

Institution	Department	Address	Contact person	Telephone/ Fax No. E-mail address	Comments on Research or Products	Comments on Contact
State and Federal Agencies						
MDOT Michigan DOT	Materials and Technology	P.O. Box 30049 8885 Ricks Road Lansing, Michigan 48909	Roger D. Till	(517) 322 5682 phone (517) 322 5203 fax tillr@state.mi.us		Project Coordinator
ODOT Ohio DOT	Bridge Bureau	25 South Front Str. Rm 516 Columbus, Ohio 43216	Mr. Steven Morton	(614) 466 4318	In the process of lab testing. Field Testing scheduled for spring. Possible visit to testing place.	Promised to send materials. Package received on Feb.7th.
DDOT Deleware DOT		Administration Center PO BOX 778 Dover, DE 19901	Mr. Chao Hu	(302) 739 4341	Performed research in cooperation with UoDE. CFRP from Tonen used.	Left message on Jan 22nd. Replied on Jan 24th. He gave contact to Prof. Michael Chajes (UoDE) who should have a report.
FDOT Florida DOT		605 Suwannee Street Tallahassee, FL 32399-0450	dr. Mohsen Shahawy	(904) 488 6179 phone (904) 488 6189 fax		Promised to send materials. Fax with address sent to him.
CDOT California DOT CALTRANS			Mrs. Beverly Mason	(916) 227 8256	Research and field applicactions in cooperation with University of California - San Diego and Hexcel Fyfe Coompany.	Contacted on March 24th following the conversation with Roger Till. Materials received through MDOT on April 9th.
CDOT California DOT CALTRANS		MS-9 Engineering Services Center 1801 30th St W Sacramento, CA 95816-5000	Mosen Soltan	(916) 227 8247	Person involved in CFRP in Caltrans.	Did not respond personally.
CDOT California DOT CALTRANS	New Tech. & Mat.; Transp. Lab.			(916) 654 9322 (916) 227 7000		Promised to respond and find proper contact person.
Air Force Wright Laboratories	Materials Directorate, Nonmetallic Materials Division	WL/XPT Building 45 2130 Eight Street Ste 1 WPAFB OH 45433-7562	Ms. Cindy Ingalls (secretary) Tech Transfer	(513) 255 2788 phone (513) 656 4572 fax ingallfs@wl.wpafb.af.mil	http://www.wl.wpafb.af.mil/stories/ss15_96.htm	Sent a fax with basic facts sheet. Gave contact to John Mistretta on (937) 255 9059
- || -	Materials Directorate, Technology Transfer Center	- || -		(513) 255 4689		Call. Refer to item 95-166.
- || -	- || -	- || -	John Mistretta Scott Thiebert (technical contact)	(937) 255 9059 J.M phone (513) 255 9018 S.T. phone	Worked with ODOT (Steven Morton). They have joint report.	Talked to Scott Thiebert. He was reluctant to help. Promised to send some materials.

US Corps of Engineers	Waterways Experiment Station	Visckburg	Edward O'Neil	(601) 634 3387 phone (601) 634 3242 fax	Did research on fiber prestressing tendons. Nothing on glued plates.	Contacted
US Corps of Engineers	Construction Engineering Research Laboratories	UASCERL ATTN: CECER-FL-M, P.O. Box 9005, Champaign, IL 61826-9005	Mr. Jonathon Trovillion	(217) 352 6511 (800) USA CERL or (800) 872 2375		
FHWA Federal Highway Administration	HNR-10 Structures Division	6300 Georgetown PK McLean, VA 22101-2296	Mr. Eric Munley	(703) 285 2438	He gave coordinates of Mitsubishi, Tonen, Sika. Two major techniques: • bonded plates • wet layout	Contacted on Jan 23. In the process of moving to new building.
Companies						
Mitsubishi Chemicals America Inc.	California Office	99 W. Tasman Drive, Suite 200, San Jose CA 95134-1712	Michihiko Sakamoto (Sales Manager Carbon Fiber)	(408) 232 6280 phone (408) 954 8494 fax	Mitsubishi Replark	Package sent to S.Y.Park. Info about adhesives faxed to S.Y.Park on March 6th.
Tonen Corporation		Place Side Bldg. 1-1-1, Hitotsubashi, Chiyoda-ku, Tokyo 100, Japan		03-3286-5104 phone 03-3286-5074 fax	Tonen Forca Tow Sheet	Materials received through US representatives.
Sika USA		201 Polito Avenue Lyndhurst, N.J. 07071	David White, P.E. Product Manager	(201) 933 8800 ext.269 (201) 933 6225 fax (800) 933 7452 toll free	Sika CarboDur - Carbon Fiber Reinforced Polymer.	Talked to David White. Promised Materials. Contacts: dr. William Spillers & Prof. Charles Dolan
Sika Corporation	US Office	2190 Gladstone Court Suite A Glendale Heights, IL 60139	Etien Frett Tech. Representative	(708) 924 7900 phone (708) 924 8508 fax (800) 933 SIKA - tech. service	Sika CarboDur - Carbon Fiber Reinforced Polymer.	Materials sent to S.Y.Park
Sika AG	Main Headquarters	P.O. Box 1300 CH-8048 Zurich/ Switzerland		01 436 40 40 phone 01 432 33 62 fax 822 254 sik ch - telex	Sika CarboDur - Carbon Fiber Reinforced Polymer.	Materials received through US representatives.
Amoco Polymers, Inc.		4500 McGinnis Ferry Road, Alpharetta, GA 30202-3914		1-800-222-2448		Contacted. Promised to send materials. No response.
Du Pont	Inquiry Center	400 Pennington Avenue P.O. Box 8116 Trenton, NJ 08650-0116		(800) 453 8527 toll free	DuPont Aramids (KEVLAR)	General data on KEVLAR received.
Ciba Composites		5115 East La Palma Avenue, Anaheim, CA 92807, USA		(714) 779 9000 Phone (714) 779 7183 Fax	M10E-AS4D Towpreg	
Hercules Advanced Materials and Systems Co.	Composite Products Group	P.O. Box 98, MS: X11T1 Magna, UT 84044-0098 USA		(801) 251 5372 Phone (800) 443 4237 Phone (801) 251 3268 Fax	Hercules Type AS4 Carbon Fiber tow	
CORDI-GEOPOLYMERE SA		16 Rue Galilee, F-02100 Saint-Quentin, France	Joseph Davidovics	+33 323 626 537 phone +33 323 676 988 fax jd20@calvacom.fr	International coordination and development of geopolimers.	Some basic materials available on Internet. Http://www.insset.u-picardie.fr/geopolymer/pub2.html#8

Craig Ballinger & Associates (coop. with Mitsubishi)		314 AYITO S. Road SE Vienna, VA 22180-2983	Mr. Craig Ballinger	(703) 938 1057 cballinger@aol.com	Cooperates with Mitsubishi. Has a lot of experience (15 years).	Gave contact to Sika (David Wight). Mentioned about tests in ODOT and GA-Tech (dr. Zurick). Sent the materials on Mitsubishi + a few papers.
H.S. Kliger & Associates, Inc.		31 Stratford Circle, Edison , NJ 08820-1815	dr.Howard S. Kliger	(908) 756 0509 phone (908) 754 5292 fax	Commercial applications of Tonen Forca Tow Sheet	He represents Tonen. Talked with secretary. Package sent to S.Y.Park.
Structural Preservation Systems, Inc.		3761 Commerce Drive, Suite 414, Baltimore, MD 21227 OR 2116 Monumental Road Baltimore, MD 21227-1633	Jay Thomas director of sales & marketing	(800) 899 1016 phone (410) 247 1016 phone (410) 247 1136 fax	Commercial applications of Tonen Forca Tow Sheet	The company using TONEN components. Package sent to S.Y.Park
Master Builders Inc.,		23700 Cnagrin Boulevard Cleveland, Ohio 44122-5554		(800) MBT-9990 (216) 831 6910	MBrace Composite Strengthening System based on Tonen Forca Tow Sheet. Commercial applications.	
Hexcel Fyfe Co.		6044 Cornerstone Court West, Suite "C", San Diego, CA 92121-4730	Scott Arnold	(619) 642 0694 (619) 642 0947 E-mail: hexcelfyfe@earthlink.net WWW: http://home.earthlink.net /~hexcelfyfe	Tyfo S Fibrwrap system based on Tonen Forca Tow Sheet. Commercial applications. Numerous strengthenings of bridges and buildings.	Fax sent on March 1st. Replied on March 3rd. Package received on April 4th.
Universities and Research Institutions						
University of Michigan	Civil and Environmental Engineering	2340 G.G. Brown Building 2350 Hayward, Ann Arbor, MI 48109-2125	Prof. Antoine Naaman	(313) 764- 1812 phone (313) 764 4292 fax naaman@engin.umich.edu		Principal Investigator of this research project
Swiss Federal Laboratories for Materials and Testing, EMPA		Uberslandstr. 129 CH-8600, Dubendorf Switzerland	Prof. Urs Meier	01-823 - 55 - 11 phone 01-823 - 62 - 44 fax urs.meier@empa.ch	Free distribution video cassette in PAL and NTSC (English) about post-strengthening of concrete structures with carbon fiber sheets.	Materials & video cassetes received on Feb. 14th.
University of Delaware	Department of Civil Engineering	Newark, DE 19716	Dr Michael Chajes	(302) 831 6056 chajes@ce.udel.edu		Called and E-mailed. Promised to send the materials.
University of Arizona			Hamid Saadatmanesh	(602) 621 2148		Contacted. Package received on Feb. 4th.
University of Wyoming			Prof. Charles Dolan	(307) 766 2857	Starting research. Nothing to send.	Contacted.
University of California		San Diego, California	Prof. Frieder Seible	(619) 534 4640		Called. Adviced to contact Mosen Soltan (Caltrans)
New Jersey Institute of Technology			dr William Spillers	(201) 596 2479	Starting research. Nothing to send.	Contacted.

RUTGERS The State Univ. of New Jersey	Department of Civil Engineering	Rutgers University Box 909 Piscataway, NJ 08855-0909	Prof. P.Balaguru	(908) 445 2232 phone (908) 445 3537 phone (908) 445 0577 fax balaguru@gandalf.rutgers.edu	They cooperate with GEOPOLYMERE	E-mail sent. No reply.
Pennsylvania State University	Architectural Engineering		Prof. Antonio Nanni	(814) 863 2084 phone (814) 863 4789 fax		
West Virginia University	Construction Facilities Center	Morgantown, WV 26506-6101	Prof. Hota V.S. GangaRao	(304) 293 7608		
Georgia Institute of Technology	School of Civil Engineering	Atlanta, GA 30332	Dr. Abdul-Hamid Zureick	(404) 894 2294 phone (404) 894 2278 fax abdul.zureick@gatech.edu		
Lawrence Tech. Institute		Southfield, Michigan	Prof.Nabil F.Grace	(810) 204 2556		
Catholic University	Civil Engineering	Washington D.C.	Dr. Lawrence Bank	(202) 319 4381 phone (202) 319 4499 fax		