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REPAIR AND STRENGTHENING OF REINFORCED CONCRETE BEAMS USING CFRP LAMINATES

Volume 1: Summary Report

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 1 (this volume) summarizes the main findings of the project. Since the adhesive-bonded plate repair and strengthening technique applies to plain, reinforced and prestressed concrete structures, as well as steel and timber structures, the experience gained during this project and the technology transfer developed cover a wide range of future applications.

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The opinions expressed in this report are those of the authors and do not necessarily reflect the views of the sponsors.

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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.

Volume 1 (this volume) summarizes the main findings of the project. Volume 2 contains an extensive literature survey with information on available technologies, contact members, latest state of knowledge, on-going projects and the like. The experimental study comprised four main parts, described respectively in Volumes 3 to 6, namely: 1) tests of RC beams strengthened in bending; 2) tests of RC beams strengthened in shear; 3) tests in bending and shear of strengthened beams under low temperature (-29°C) and high amplitude cyclic loading; and 4) repeated freeze-thaw exposure of strengthened beams followed by their test in bending. In each experimental part, results are analyzed, compared, discussed, and key conclusions drawn. Volume 7 provides technical specifications based on information provided by he manufacturers of the two CFRP systems used and augmented by the experience accrued during the course of this investigation.

Since the adhesive-bonded plate repair and strengthening technique applies to plain, reinforced and prestressed concrete structures, as well as steel and timber structures, the experience gained during this project and the technology transfer developed cover a wide range of future applications.

1. INTRODUCTION-MOTIVATION

1.1 Background

The maintenance of highway superstructures, particularly bridges, consumes a significant portion of available maintenance funds in the US and other countries as well. Thus the development of effective repair and retrofit techniques has become an essential goal of every federal or state agency responsible for maintenance of such civil infrastructures. These techniques are also increasingly needed to repair damage due to normal use and to environmental factors.

The use of non-metallic reinforcements, especially fiber reinforced plastics or polymers (FRP), utilizing high performance fibers such as carbon, glass, aramid (Kevlar), and others, is seen primarily as a means to avoid corrosion problems otherwise encountered in concrete structures when using conventional steel reinforcing bars or prestressing tendons. These advanced composites are likely to play a significant role in future construction applications particularly in the strengthening and rehabilitation of existing bridges.

Among the many possible alternatives considered with FRP reinforcements, the use of adhesively bonded laminates (also called sheets, tow-sheets, plates), primarily made of carbon fiber reinforced plastics (CFRP), form the basis of a new technology that is being increasingly considered for the repair and strengthening of bridges and highway superstructures. In this technique, an FRP laminate is glued (adhesively bonded) directly to the tensile face (extreme fiber) of a concrete beam and functions as additional tensile reinforcement. Numerous applications have already taken place in Japan and Western Europe and the number of applications is growing in the US and Canada.

Compared to bonded steel plates where length and weight are limitations, CFRP plates offer the following advantages: they are thin, lightweight, non-corrosive, and can be virtually delivered in any length. While their unit cost is higher than that of steel plates, their easier handling in the field makes them cost competitive.

The number of potential applications of the "bonded plate" technique for repair or strengthening purposes is staggering. Examples include: 1) repair of bridge beams damaged by the occasional impact of over-sized trucks; 2) retrofit of bridge beams in which part of the reinforcement was lost due to corrosion; 3) strengthening of bridge beams such as needed when permissible truck loads are increased; 4) strengthening of slab bridges; 5) tunnel lining; 6) strengthening of steel or wood beam; 7) extending the life of utility poles by wrapping around FRP sheets; and 8) repair of aging water and sewer pipes.

The study described in this report was carried out under a project titled: *"Repair and Strengthening of Reinforced and Prestressed Concrete Beams using CFRP Glued-on Plates"* funded jointly by the Michigan Department of Transportation (MDOT Contract No. 96-1067BAB) and by the Great Lakes Center of Truck and Transit Research (GLCTTR). It was aimed at providing experimental verification and recommendations for implementation of a new technology, in which thin carbon fiber reinforced plastic or polymeric (CFRP) laminates are adhesively bonded to the surface of concrete beams in order to strengthen them.

1.2 Main Objectives

The primary objectives of the project were:

- To ascertain the applicability of Carbon Fiber Reinforced Plastic (CFRP) bonded laminates for repair and strengthening of reinforced concrete beams;
- To synthesize existing knowledge and develop procedures for implementation in the field;
- To identify key parameters to insure successful performance;
- To adapt this technique to the specific conditions encountered in the state of Michigan.

1.3 Reports

To achieve the above objectives, several tasks were undertaken over a period of 30 months and are described in the following series of reports having the same general title. The subtitle of each report gives an idea of the different parts of the experimental program carried out. The first report is the present one.

1. Repair and Strengthening of Reinforced Concrete Beams Using Adhesive Bonded CFRP Laminates:
   Vol. 1 Summary Report

2. Repair and Strengthening of Reinforced Concrete Beams Using Adhesive Bonded CFRP Laminates:
   Vol. 2 Literature Review
   This report contains a literature review and a comprehensive synthesis of the latest state of knowledge on the adhesive bonded FRP laminate technique.

3. Repair and Strengthening of Reinforced Concrete Beams Using Adhesive Bonded CFRP Laminates:
   Vol. 3 Behavior of Beams Strengthened for Bending

4. Repair and Strengthening of Reinforced Concrete Beams Using Adhesive Bonded CFRP Laminates:
   Vol. 4 Behavior of Beams Strengthened for Shear

5. Repair and Strengthening of Reinforced Concrete Beams Using Adhesive Bonded CFRP Laminates:
   Vol. 5 Behavior of Beams under Cyclic Loading at Low Temperature

6. Repair and Strengthening of Reinforced Concrete Beams Using Adhesive Bonded CFRP Laminates:
   Vol. 6 Behavior of Beams Subjected to Freeze-Thaw Tests

7. Repair and Strengthening of Reinforced Concrete Beams Using Adhesive Bonded CFRP Laminates:
   Vol. 7 Technical Specifications

Since the adhesive-bonded plate repair and strengthening technique applies to plain, reinforced and prestressed concrete structures, as well as steel and timber structures, the experience gained during this project and the technology transfer developed cover a wide range of future applications.

2. LITERATURE REVIEW (VOLUME 2)

2.1 Introduction

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 [ACI 440, 1996].

Composite plates usually are epoxy-bonded to the tension flange and/or web of slabs or girders, increasing their strength in bending and/or shear, and their stiffness. Compared to external post-tensioning, this technique eliminate the need for special anchorages.

Fiber Reinforced Plastic or Polymeric (FRP) composites are defined, in a most generic way, as a polymeric matrix that is reinforced with strong stiff fibers. Unidirectional FRP sheets, plates, or laminates are made of Carbon (CFRP), Glass (GFRP) or Aramid (AFRP) fibers bonded together with a polymer matrix (e.g. epoxy, polyester, vinyl ester). A laminate is made by stacking one or a number of thin layers of fibers and matrix and consolidating them into the desired thickness.

Among existing FRP laminates, CFRPs offer the highest potential as a replacement of steel in typical strengthening applications, because of their combine properties of very high strength, high stiffness, outstanding fatigue performance, and little sensitivity to stress-rupture with time.

2.2 Organization of Volume 2

Volume 2 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 bond 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.

Chapter 4 surveys first a large number of research projects and field applications of adhesive-bonded 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 were 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, that 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 as described next.

2.3 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 were classified as follows:

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

A summary of contacts (name, address, telephone number) was developed for current and future reference and was included in Table 7.1 of Appendix A of Volume 2. For convenience the summary of research and applications was grouped according to research teams or organizations working together. An appropriate reference code was assigned to each group.

2.4 Summary of Main Findings

- 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.

- Among different FRP laminates reviewed, Carbon FRP composites seem 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 a 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.

- So far, no standardized guidelines have been developed for this technique. To utilize a strengthening system requires strict following of the procedures recommended by each commercial product manufacturer.

- 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.

- Field testing 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 compensated by the cost savings on labor due to ease of application.

- 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.

3. BEHAVIOR OF BEAMS STRENGTHENED FOR BENDING (VOLUME 3)

3.1 Experimental Program

The part of the investigation deals with reinforced concrete beams strengthened in bending. The CFRP laminates are bonded to the extreme tensile face of the beam with fibers oriented along the longitudinal axis of the beam. Experimental results are presented, analyzed, compared, and discussed.

The experimental program comprised fourteen reinforced concrete T-beams (Table 1a). The test parameters included two levels of steel reinforcement ratio before strengthening, and up to four strengthening levels. Two commercially available strengthening systems were tested, the Sika CFRP plate system (CarboDur), and the Tonen CFRP sheet system. Other selective parameters investigated included two different concrete covers; two conditions of cover preparation, three different end anchorage systems of the glued-on sheets, and pre-loading pre-yielding of the beam prior to strengthening. Details of the test parameters are given next. Key results are summarized in Table 1b.

3.2 Test Parameters

The test parameters included the existing steel reinforcement ratio before strengthening, and the strengthening level. For each steel reinforcement ratio, a control beam was tested and compared with CFRP bonded beams having different strengthening levels. The steel reinforcement ratios of the control beams were respectively $0.27\rho_{max}$ and $0.54\rho_{max}$, where the maximum reinforcement ratio, ρ_{max}, is defined as per the AASHTO or ACI Code to represent 75% of the balanced ratio. The strengthening level (that corresponds to the number of CFRP sheets) was determined assuming the total reinforcement of steel and CFRP will not exceed the maximum reinforcement ratio allowed for the beam by the AASHTO Code based on the assumption that the CFRP sheet will fail in tension.

Two strengthening systems were tested: 1) the Sika CFRP plate system (CarboDur), and 2) the Tonen CFRP sheet system. The Sika plate was about 1.2 mm thick and quite rigid, while the Tonen sheet was 0.11 mm thick and flexible like wall paper. The Tonen system was used for 12 beams and the Sika system for 2 beams. For Beam No. 8, the glued-on Sika CFRP plate had a width of 40 mm, which is equivalent in tensile strength to 2 layers of Tonen CFRP sheets (Forca Tow sheet). Following testing, Beam No. 8 was in very good shape even after the interfacial shear failure of concrete. There was no spalling of concrete cover even though the reinforcing bars had yielded and the 40 mm wide CFRP plate was completely delaminated. Beam No. 8 was later re-used as Beam No. 8-1, this time with a CFRP plate 100 mm wide to evaluate a different bond width and strengthening levels.

For one selected set of parameters, two different concrete covers and cover conditions were investigated to study the influence of concrete cover on strengthening effect and mode of failure. The normal clear cover of concrete was taken as 50 mm. For one beam a concrete clear cover of 25 mm was used. Another beam was cast with an initial 25 mm clear concrete cover; however an additional 25 mm repair mortar cover was added prior to strengthening to simulate damaged concrete in real beams.

Table 1a Parameters and variables for the bending tests ($f'_c = 55.2$ MPa).

Beam No.	Test parameter	Reinforcement ratio, ρ	$A_{s(used)}$ mm^2	M_n/M_{max} %	Forca Tow sheet FTS-C1-30	Strengthening ratio[1] % ()[2]	CarboDur strip (1 layer)	Strengthening ratio[1] % ()[2]
1	Steel reinforcement ratio & Strengthening level	$0.27\rho_{max}$	2#10 2#13 A_s=400	29	0	0 (29)		
2					1 layer	12 (41)		
3					2 layers	24 (52)		
4					4 layers	47 (75)		
5		$0.54\rho_{max}$	4#16 A_s=800	57	0	0 (57)		
6					1 layer	12 (68)		
7					2 layers	24 (80)		
8	Different system (Sika)	$0.54\rho_{max}$	4#16 A_s=800	57			width= 40 mm	22 (78)
8-1		$0.54\rho_{max}$	4#16 A_s=800	57			width= 100 mm	60 (113)
9	Repaired concrete over	$0.54\rho_{max}$	4#16 A_s=800	57	2 layers	24 (80)		
10	Extended end nchorage	$0.54\rho_{max}$	4#16 A_s=800	57	2 layers	24 (80)		
11	Pre-loading	$0.54\rho_{max}$	4#16 A_s=800	57	2 layers	24 (80)		
12	Concrete cover depth 25 mm	$0.54\rho_{max}$	4#16 A_s=800	57	2 layers	22 (78)		
13	Cleaned surface	$0.54\rho_{max}$	4#16 A_s=800	57	2 layers	24 (80)		
14	No anchorage	$0.54\rho_{max}$	4#16 A_s=800	57	2 layers	24 (80)		

Note: 1: $M_{FRP}/M_{max.}$x100

2: $(M_{As}+M_{FRP})/M_{max.}$x100, $M_{max.} = M_n$ (when $A_s = A_{smax}$), ($f'_c = 55.2$ MPa, $f_y = 455$ MPa, $A_{smax} = 1490$ mm^2)

All the above values are calculated

Table 1b Summary of main results of bending tests.

Beam No.	Test parameter	Reinforcement ratio	No. of CFRP layer	Failure mode[1]	Ultimate load kN	Strengthening ratio[2] % ( )[3]	Ultimate deflection mm
1	Steel reinforcement ratio & strengthening level	$0.27\rho_{max}$	0	Steel yielding	114.8	0	164
2			1	CFRP rupture	135.0	18 (41)	83
3			2	Interface failure	140.4	22 (81)	56
4			4	Interface failure	160.7	40 (160)	49
5		$0.54\rho_{max}$	0	Steel yielding	188.0	0	88
6			1	Interface failure	209.9	12 (21)	77
7			2	Interface failure	222.0	16 (41)	51
8	Different system (Sika)	$0.54\rho_{max}$	40 mm	Interface failure	209.2	11 (39)	46
8-1			100 mm	Interface failure	250.9	33 (100)	41
9	Repaired concrete cover		2	Interface bond failure	208.2	11 (41)	73
10	Extended end anchorage			Interface failure	220.4	17 (41)	59
11	Pre-loading			Inter-laminar failure	226.2	20 (41)	119
12	Concrete cover depth			Interface failure	221.2	18 (37)	69
13	Cleaned surface			Interface failure	230.8	23 (41)	60
14	No anchorage			Interface failure	215.1	14 (41)	57

1: Steel yielding: Compression failure of top concrete long after reinforcement yielding
CFRP rupture: Tensile failure of CFRP sheet
Interface failure: Interfacial shear failure of concrete just above the epoxy adhesive.
Interface bond failure: Interfacial bond failure between the repair mortar and the existing concrete
Inter-laminar failure: Inter-laminar shear failure between glued-on CFRP sheets

2: Actual strengthening ratio compared to control beam (Beam No. 1 or No. 5)

3: Design strengthening ratio compared to control beam based on the assumption of CFRP tensile failure

To evaluate different anchorage systems, three different anchorage conditions were provided for beams using the Tonen system. One beam had extended end anchorage which means that the glued-on CFRP sheets were extended up to about 50 mm from the supports, without adding the U-shaped wrapped-around end anchorage. Another beam had neither a U-shaped wrapped-around end anchorage nor an extended end anchorage. All other beams strengthened with Tonen sheets had, at both ends, a 100 mm wide U-shaped wrapped-around end anchorage perpendicular to the longitudinal CFRP sheets. The beams strengthened with the Sika system did not have a wrapped end anchorage.

One beam was pre-loaded slightly beyond yielding of steel reinforcing bars to investigate the influence of loading history before the application of CFRP plate. The permanent deflection and maximum crack width at unloading in the pre-cracked beam were 25 mm and 0.9 mm, respectively.

For all beams except one, the concrete surface to be glued on was prepared, for better bond, by grinding with a disk grinder according to the recommendations of the supplier of the strengthening system used. For Beam No. 13, the surface of concrete was simply cleaned with a vacuum cleaner and wiped with a clean cloth to remove any dust. The test parameters and main results are described in Tables 1a and 1b.

3.3 Strengthening Level and Strengthening Ratio

For the Tonen thin sheet system, the term "different strengthening level" referred to a different number of CFRP sheets used, such as one, two, or four. For the Sika system (thicker plate laminate), a "different strengthening level" implied different widths of the CFRP plate used.

The strengthening ratio of a beam is defined as the increment of nominal bending resistance induced by strengthening to the nominal bending resistance of the beam assuming it has a reinforcement ratio $\rho = \rho_{max}$, where ρ_{max} is the maximum reinforcement ratio for under-reinforced sections according to the AASHTO or ACI Codes.

3.4 Conclusions

Based on the observation and analysis of the experimental test results the following conclusions were drawn.

1. The strengthening technique using externally bonded CFRP sheets or plates can significantly improve the ultimate loading capacity of reinforced concrete beams; however, their ultimate deflection is reduced. Moreover, the strengthened beams had, after failure or delamination of the CFRP sheets, a minimum loading capacity and ductility which were almost same as those of the control beam.

2. Strengthening with CFRP sheets can inhibit the growth of large cracks by helping distribute a large number of smaller cracks; it also protect the steel reinforcement from ingress of corrosive agents.

3. In general, normally strengthened beams fail by interfacial shear failure (delamination) within the concrete, instead of by tensile failure of the CFRP sheet or plate.

4. In normally strengthened beams, the increment in ultimate load obtained by strengthening was almost proportional to the strengthening level or number of CFRP sheets. However, this direct relationship should be further confirmed experimentally in beams with strengthening levels and reinforcement ratios higher that those investigated in this study.

5. For a given reinforcement ratio, the ultimate load capacity increases with the strengthening level, or the number of CFRP sheets. However, the steel reinforcement ratio of the reinforced concrete beam to be strengthened, does not seem to have a significant effect on the increment of load at ultimate achieved by strengthening. This implies that the lower the reinforcement ratio, the higher the strengthening effect in terms of percent increase in ultimate load capacity.

6. The ultimate deflection of strengthened beams decreased in comparison to the control beam as the strengthening level increased, thus leading to a lower ductility. This is one of the disadvantages of beams strengthened using CFRP sheets. However, the strengthened beams had, after failure or delamination of the CFRP sheets, a minimum loading capacity and ductility which were almost same as those of the control beam.

7. Beams using the strengthening system with CFRP plate (Sika system) showed the same load versus deflection response as beams using the strengthening system with CFRP sheet (Tonen system), even though the tensile modulus of the CFRP plate was two thirds that of the CFRP sheet. In this investigation where non-trained students were involved, it was found that the system using CFRP plate is easier and more convenient to apply for flexural strengthening than that using the CFRP sheet.

8. The strengthened beam with a smaller concrete cover had slightly higher ultimate load and considerably larger ultimate deflection than the control beam with normal concrete cover.

9. The beam strengthened after having a repaired concrete cover failed by gradual interlaminar debonding at the interface between existing concrete and repair mortar; it led to a ductile behavior, but did not achieve an adequate level of strengthening.

10. Using a U-shaped end anchorage of the CFRP sheet did not help attain higher ultimate loads or deflections, in comparison to having no anchorage. However, extending the sheet up to the supports led to slightly higher ultimate load and deflection. Therefore, the extended end anchorage system is recommended because it is easier to apply.

11. Preparing the concrete surface by grinding prior to the application of CFRP sheets was not more effective than simply vacuum cleaning and wiping the surface. However this conclusion should be further confirmed in real beams with deteriorated concrete surfaces.

12. Pre-loading and pre-cracking a beam beyond reinforcement yielding had no serious influence on the strengthening effect. Therefore, the CFRP glued-on strengthening technique can be applied even to severely damaged beams.

13. The beam that failed by CFRP sheet delamination and was damaged due to severe concrete cover spalling had, upon reloading, the same ultimate load and deflection as the control beam, even though the damage to the cover was severe. This fact can insure some

minimum safety level for beams strengthened using CFRP sheets, should failure by delamination or tension of the sheet occur.

14. Based on the limited number of tests carried out, it seems that the contribution of the shear resistance of concrete to the strength of the interface, linearly increases with the strengthening level. For this conclusion, the interface shear stress of concrete was calculated based on the assumption of equal shear stress along the shear span.

3.5 General Recommendation

Although numerous factors can affect the extent to which a reinforced concrete beam can be strengthened for bending using adhesively bonded CFRP laminates, it seems safe to design for increments of bending strength not exceeding about 20% of the nominal bending resistance of the beam calculated assuming a reinforcement ratio equal to ρ_{max}, where ρ_{max} is the maximum reinforcement ratio defined in the ACI Building Code or the AASHTO Specification. A smaller concrete cover is generally better and there is no need for special anchorages beyond extending the laminate to close to the support or point of zero moment.

6. BEHAVIOR OF BEAMS STRENGTHENED FOR SHEAR (VOLUME 4)

4.1 Experimental Program

For this part of the experimental investigation, the CFRP laminates, when used, are bonded to the web of a beam (symmetrically on each side) with their fibers oriented normally to the longitudinal axis of the beam. The two strengthening systems used for the bending tests (the Sika CFRP plate system (CarboDur), and the Tonen CFRP sheet system) were also used for the shear tests. The Tonen sheet was wrapped in a U-shape around the bottom of the beam and fully covered the two webs. With the Sika plate, strips were cut and bonded symmetrically to the two web faces, along their entire depth; the width and spacing of the strips were determined to provide a strength equivalent to the one layer of Tonen CFRP sheet.

The experimental program comprised three rectangular concrete beams and three T-beams. The test parameters included selectively, two different shear-span ratios (2.5 for the rectangular beams and 3.5 for the T-beams), two levels of longitudinal steel reinforcement ratio before strengthening, and two shear reinforcement levels. The rectangular beams were fabricated without steel stirrups and reinforced for shear using CFRP bonded laminates only. The T-beams were provided with some steel stirrups and strengthened in both bending and shear. The test parameters are summarized in Table 2a and key results are given in Table 2b. The main conclusions are summarized next.

Table 2a Parameters and variables for shear tests.

Beam No.	*Section* type	*Shear reinforcement* (A_v) Stirrup	CFRP sheet	*Shear span-to-depth ratio* (a/d)	*Longitudinal Steel reinforcement ratio* (ρ)	*Strengthening*
1	102x254 Rect.-section	None	None	2.5	1.41 ρ_{max}	Control
2		None	$A_{v(FRP)}$ Tonen sheet	2.5	1.41 ρ_{max}	Shear
3		None	$A_{v(FRP)}$ Sika plate	2.5	1.41 ρ_{max}	Shear
4	304x304 T-section	0.91 $A_{v(max)}$	None	3.5	0.89 ρ_{max}	Control
5		0.91 $A_{v(max)}$	$A_{v(FRP)}$ Tonen sheet	3.5	0.89 ρ_{max}	Shear & Bending
6		0.91 $A_{v(max)}$	$A_{v(FRP)}$ Sika plate	3.5	0.89 ρ_{max}	Shear & Bending

Note: 1. Actual concrete compressive strength, f'_c = 25.4 MPa. Actual steel yield stress, f_y = 496 MPa and 483 MPa for rectangular and T sections respectively.
2. Maximum shear reinforcement ratio, $A_{v(max)}$, is for maximum longitudinal reinforcement ratio, ρ_{max}.

4.2 Conclusions

1. Strengthening for shear using externally bonded CFRP laminates can significantly improve the ultimate loading capacity of reinforced concrete beams having deficiency in shear. Because shear failure is delayed, their ultimate deflection is also significantly increased. In beams insufficiently reinforced for shear, the use of CFRP shear strengthening led to an increase in load capacity of at least 30%.

2. The Tonen CFRP sheet led to a higher shear strengthening effect than the Sika CFRP strips because of its larger bond area and because it was better anchored by wrapping around the web (U-shape). The development of L or Z shaped Sika CFRP plates should improve the strip anchorage and contribute to its increased efficiency.

3. It was generally observed that shear strengthened beams fail by delamination of the CFRP sheet or plate used for shear strengthening, resulting in shear failure of concrete.

4. The tensile stresses generated in the bonded CFRP laminate used for shear are very low compared to their tensile strengths. In this study they were about one twentieth and one seventh the tensile strength of CFRP Tonen sheet and Sika plate, respectively.

Table 2b Summary of main results of the shear tests.

Beam No.	Section type	Shear reinforcement (A_v)		a/d	Longitudinal Reinforce-ment	Failure Mode	Ultimate load, kN	Ultimate deflection, mm	Predicted failure load (bending failure)[1] kN	Predicted failure load (shear failure)[2] kN
		Stirrup	CFRP							
1	Rectangular	None	None	2.5	1.41 ρ_{max}	Shear failure	51.8	3.0	106.75	31.14
2	Rectangular	None	CFRP sheet (Tonen)	2.5	1.41 ρ_{max}	Steel yielding & Delamination	130.5	7.4	106.75	615.16
3	Rectangular	None	CFRP strip (Sika)	2.5	1.41 ρ_{max}	Delamination shear failure	88.1	4.3	106.75	1001
4	T-section	0.91 A_v max (64.5 mm^2)	None	3.5	0.89 ρ_{max}	Steel yielding & shear failure	164.2	15.5	161.75	166.71
5	T-section	0.91 A_v max (64.5 mm^2)	CFRP sheet (Tonen)	3.5	0.89 ρ_{max}	Steel yielding & Delamination	240.2	12.2	257.15	745.75
6	T-section	0.91 A_v max (64.5 mm^2)	CFRP strip (Sika)	3.5	0.89 ρ_{max}	Delamination shear failure	214.5	9.9	301.35	1131.75

Note: 1. See Appendix in Volume 4 for detailed calculations

2. See Appendix in Volume 4 for detailed calculations

5. In this study, shear stresses of concrete at onset of delamination of CFRP laminate used for shear were about $0.06\sqrt{f'_c}$ and $0.10\sqrt{f'_c}$ for Tonen CFRP sheet and Sika CFRP plate, respectively. (These were the average vertical shear stresses calculated from strain gages placed on the CFRP laminate used for shear strengthening).

6. The strains in the steel stirrups and the CFRP sheets or plates used for shear varied linearly with the applied load in the range following shear cracking and before onset of delamination.

7. The stresses in the CFRP sheet or plate used for flexure increased linearly with the load and deflection in the range prior to delamination of CFRP sheet and plates used for shear.

5. BEHAVIOR OF BEAMS UNDER CYCLIC LOADING AT LOW TEMPERATURE (VOLUME 5)

5.1 Introduction - Description

Four reinforced concrete beams strengthened with CFRP sheets were designed, prepared and tested in bending under low temperature conditions (-29°C). Two short beams designed to be shear critical were strengthened for shear with the CFRP Tonen sheet system. They were tested under center point loading. The two other beams had longer spans; they were designed to be bending critical and were strengthened using the CFRP Sika plate system; they were tested under four points loading. In each case one beam was tested monotonically and the other beam was tested in cyclic fatigue. The amplitude of the cyclic load was taken as 10 to 80% of the failure load observed in the monotonic test. The test parameters and key results are given in Tables 3a and 3b respectively. Details are given in Volume 5. In particular the procedure followed to test the specimens under low temperature conditions is described and the design of a controller system developed to maintain the temperature environment is explained. Also a design example is provided.

Table 3a Parameters for low temperature and fatigue loading tests.

Beam Description	*Temperature*	*Type of Loading*
Bending Testing	-29°C	Monotonic to failure
Bending Testing	-29°C	High amplitude cycling (10% to 80% of ultimate bending strength)
Shear Testing	-29°C	Monotonic to failure
Shear Testing	-29°C	High amplitude cycling (10% to 80% of ultimate shear strength)

Table 3.b Summary of main results for the low temperature and fatigue loading tests.

Beam	Parameter	Predicted load (KN)	Peak Load (KN) Range (%)	Max. Shear (KN)	Max. Moment (KN-m)	Type of Failure
1	Shear Mono-tonic	246	206	103	37	Concrete shear crack from load point to supports. Debonding of the CFRP sheet along the major crack.
2	Shear Fatigue	N.A.	20.6-165 10-80%	82.4	29	Total # cycles = 43083 Fatigue failure of the bottom layer of steel. A vertical crack of the entire concrete section and rupture of the CFRP sheet under the load point.
3	Flexure Mono-tonic	93	131	65.7	50	Partial debonding of the CFRP plate. Interfacial delamination of the CFRP plate at the extreme end.
4	Flexure Fatigue	N.A.	13.1-105 10-80% *9.4-75%	52.6	40	# of cycles = 85,000
		N.A.	13.1-118 10-90% *9.4-85%	59.1	45	# of cycles = 61,000 Total # cycles = 146,000
		N.A.	13.1-131 10-100% *9.4-94%	65.7	50	# of cycles = 9,500 Total # cycles = 155,500
		93	Monotonic 139.15	69.6	53	Total # cycles = 155,500 Partial debonding of the CFRP plate. Interfacial delamination of the CFRP plate at the extreme end. Crushing of concrete at the top layer midspan.

* Modified range according to maximum load of the monotonic test of the "fatigue" specimen.

N.A. Not Applicable.

5.2 Conclusions

1. Prior tests (seen Volume 2) showed that the failure mode of RC beams strengthened with CFRP Sika plates and loaded in monotonic bending at normal room temperature was by delamination of the CFRP plate. The limited tests carried out at low temperature (-29^{o}C) and cyclic fatigue loading, suggest that the failure mode remains the same, that is by delamination.

2. The strain data of the cyclic fatigue test in bending showed redistribution of strains (thus stresses) in the CFRP plate with an increasing number of cycles. A more uniform strain pattern was achieved suggesting that slow delamination of the plate occurred during cycling. Higher strains at the end of the plate confirmed the extension of delamination toward that section and subsequent delamination failure at that section.

3. Values of the interfacial shear stress from the strains recorded by the gages showed that the interfacial strength at failure (1.62 and 1.58 MPa) was similar for both the monotonically tested flexure beam and the fatigue tested flexure beam after 155,500 cycles.

4. Failure in the shear beam subjected to monotonic loading at -29^{o}C occurred by shear delamination of the CFRP Tonen sheet along the web surfaces, followed by shear failure of the concrete across the section. The shear delamination seems to have initiated with the propagation of a diagonal shear crack within the concrete that extended from the load point to the support.

5. Failure in the shear beam that was subjected to cyclic fatigue loading at -29^{o}C was initiated by failure of one of the reinforcing bars in the first layer of steel, which was shortly followed by failure of two additional bars. Subsequent analysis suggested that failure of the rebars was by brittle fracture due to the low temperature at which the tests were performed. It was considered that a combination of low temperature and fatigue contributed to this type of failure.

6. Increase in the shear strain obtained with cyclic shear loading from the rosette gage placed at midspan along the vertical axis of the beam suggest that some delamination and cracking were occurring at that section. It is likely that a shear failure would have occurred in a manner similar to the monotonically tested beam, should failure of the reinforcing bar not have occurred.

5.3 Main Conclusion

The main objective of this part of the research was to ascertain that strengthening by CFRP adhesive bonded laminates remains reliable at low temperatures, such as those experienced in the State of Michigan. The limited number of tests carried out in this study suggests that temperatures as low as -29^{o}C do not affect the behavior of the CFRP strengthening system itself, or the interface on the laminate side.

6. BEHAVIOR OF BEAMS SUBJECTED TO FREEZE-THAW CYCLES (VOLUME 6)

6.1 Test Parameters

The experimental program comprised forty-eight reinforced concrete beams. The beams were prismatic with a cross section of 76.2x76.2 mm and a length of 1016 mm. The beams were minimally reinforced to insure safe handling. The specimens were subjected to up to 300 freeze-thaw cycles. For every parameter, three beams were tested in bending at 0, 100, 200 and 300 cycles, under four points bending. Parameters investigated were two different adhesive systems, the Tonen CFRP sheet system (MBrace), and the Sika CFRP system (Sikadur); and a cracking stage where precracking is meant to simulate the cracking conditions in the field prior to strengthening. It was expected that water would enter into the cracks during the thawing cycle and expand with subsequent freezing, resulting in a more critical situation for the performance of the strengthening system. The influence of the presence of cracks was compared with that of specimens without initial cracks. Control specimens (RC beams with no externally bonded CFRP laminate) were also subjected to 0, 100, 200 and 300 freeze-thaw cycles and tested for comparison. The tests parameters are summarized in Table 4a and the main results are given in Table 4b.

Volume 6 provides all the details of this part of the study. In addition, Volume 6 contains a review of the limited literature pertinent to the subject and two appendices, one giving a detailed design example of a reinforced concrete beam strengthened with CFRP laminates, and the second providing a discussion of different approaches to compute bond shear stress at the interface between the CFRP laminate and concrete.

Table 4a Parameters of the freeze-thaw (F.T.) beam tests.

Parameters	*Number of Freeze-thaw cycles*				*Total number of specimens* (48)
	0	100	200	300	
Control beam (Precracked, no CFRP)	3	3	3	3	12
Sika System (Precracked beams)	3	3	3	3	12
Tonen System (Precracked beams)	3	3	3	3	12
Tonen System (not precracked beams)	3	3	3	3	12

6.2 Conclusions

1. For the control specimens no decrease in the moment capacity or shear strength due to the freeze-thaw (F.T.) cycles was observed. However, a decrease in the maximum deflection was observed.

Table 4b Summary of the main results from the freeze-thaw beam tests.

Number of Cycles	Parameter	Peak Load (KN)	Deflection at Failure (mm)	Delamination Length (mm)	Type of Failure
0 cycles	No CFRP (precracked beam)	2.65	7.62	0.00	Yield and fracture of reinforcement
		2.52	7.11	0.00	Yield and fracture of reinforcement
		2.64	8.03	0.00	Yield and fracture of reinforcement
	Tonen sheet (precracked beam)	19.54	10.85	101.60	Shear-delamination (crack at 30°angle)
		20.49	12.37	279.40	Shear-delamination.
		19.90	11.15	69.85	Shear-delamination.
	Tonen sheet (non-precracked)	16.79	9.50	196.85	Flexure-delamination
		17.81	9.96	165.10	Flexure-delamination
		17.04	9.55	139.70	Flexure-delamination
	Sika sheet (precracked beam)	22.02	8.76	0.00	Shear (crack length = 178 mm)
		21.29	8.10	0.00	Shear
		23.99	9.58	254.00	Shear-delamination
100 cycles	No CFRP (precracked beam)	2.85	7.62	0.00	Yield and fracture of reinforcement
		2.81	7.11	0.00	Yield and fracture of reinforcement
		2.73	9.65	0.00	Yield and fracture of reinforcement
	Tonen sheet (precracked beam)	16.09	9.65	127.00	Shear-delamination (45°angle)
		15.81	9.91	152.40	Shear-delamination
		15.93	9.65	165.10	Shear-delamination-flexure (50°angle)
	Tonen sheet (non-precracked)	16.46	10.16	152.40	Shear-delamination
		16.46	9.40	177.80	Shear-delamination
		10.98	8.64	139.70	Shear-delamination
	Sika sheet (precracked beam)	19.55	7.11	0.00	Shear (crack length =229 mm)
		20.39	7.87	0.00	Shear (crack length = 229 mm)
		20.18	7.62	0.00	Shear
200 cycles	No CFRP (precracked beam)	2.94	6.86	0.00	Yield and fracture of reinforcement
		2.96	6.86	0.00	Yield and fracture of reinforcement
		2.53	7.62	0.00	Yield and fracture of reinforcement
	Tonen sheet (precracked beam)	15.40	6.10	139.70	Shear-delamination (40°angle)
		13.34	6.86	0.00	Shear-delamination
		13.78	7.62	215.90	Shear-delamination (60°angle)
	Tonen sheet (non-precracked)	14.06	7.37	139.70	Flexure-delamination
		13.34	7.37	177.80	Shear-delamination (45°angle)
		14.44	7.62	203.20	Flexure-delamination (75°angle)

	Sika sheet (precracked beam)	19.57	7.62	203.20	Delamination-flexure (25°angle)
		19.64	7.37	241.30	Delamination-shear (45°angle)
		19.49	7.62	0.00	Shear (crack length = 203 mm)
300 cycles	No CFRP (precracked beam)	2.94	6.35	0.00	Yield and fracture of reinforcement
		2.49	6.35	0.00	Yield and fracture of reinforcement
		2.75	6.10	0.00	Yield and fracture of reinforcement
	Tonen sheet (precracked beam)	12.66	6.86	177.80	Flexure-delamination
		12.45	6.35	165.10	Flexure-delamination
		12.13	6.35	190.50	Shear-delamination (40°angle)
	Tonen sheet (non-precracked)	13.22	7.87	152.40	Shear-delamination
		14.52	7.62	177.80	Shear-delamination (35°angle)
		13.74	8.13	0.00	Shear-delamination
	Sika sheet (precracked beam)	21.88	8.64	177.80	Shear-delamination (35° angle)
		21.33	8.38	241.30	Shear-delamination flexure (25°angle)
		21.14	7.62	254.00	Flexure-delamination (30° angle)

2. For specimens strengthened with CFRP sheets an overall decrease in the moment capacity as well as the maximum deflection was observed with an increase in number of freeze-thaw cycles. Precracked beams using the Tonen system presented the higher rate of decrease of moment capacity (38% average for 300 F.T. cycles). Non-precracked beams also strengthened with the Tonen system led to an average decrease of 20% for 300 F.T. cycles.

3. The maximum moment capacity of beams strengthened with the Sika system decreased 13% on average for 200 F.T. cycles and 4% average for 300 F.T. cycles. This variation was attributed to the influence of different type of failure modes.

4. The average deflection at maximum load was very sensitive to the effect of the freeze-thaw cycles and the cracking condition. For the Tonen precracked beams a reduction of 43% in deflection was found after 300 F.T. cycles whereas for the Tonen non-precracked beams the decrease was of 19%. Beams using the Sika system showed a smaller rate of decrease in deflection at maximum load (15% average for 200 F.T. cycles and 7% for 300 F.T. cycles)

5. With the Tonen system, the values of normalized shear stress (v_n) for the same number of freeze-thaw cycles were higher for the flexure-delamination failure than for the shear-delamination failure. It was concluded that shear cracks accelerate the interfacial crack propagation.

6. With the Tonen system, precracking the beam influences the decrease in the average normalized shear stress with the freeze-thaw cycles. For 300 freeze-thaw cycles, precracked beams had a decrease of 39% (compared with the strength at zero F.T. cycles) whereas the decrease for the non precracked beams was 22%. However the normalized shear stress after 300 F.T. cycles remained almost the same: $v = 0.20\sqrt{f'_c}$ for precracked beams, and $v = 0.19\sqrt{f'_c}$ for non-precracked beams. It can be shown that at zero F.T. cycles the cracking condition influences the capacity of the beam, whereas after 300 F.T. cycles, the freezing and thawing effect dominates.

7. For the Sika system, ignoring vertical shear failure, the decrease in the normalized average shear stress at failure load due to the effect of the freeze-thaw cycles seemed to be less significant than for the Tonen system. A decrease of 10% was observed for 300 freeze-thaw cycles, leading to a value of $0.36\sqrt{f'_c}$.

8. For both strengthening systems (Tonen and Sika), the delamination length found in specimens that failed either by shear-delamination or flexure-delamination was located between the end of the CFRP laminate and the maximum bending moment region.

9. The delamination length was quite uniform for both strengthening systems. For the Tonen system, values of delamination length varied between 140 to 180 mm. For the Sika system, the range was even more narrow, 220-250 mm. No influence of either the number of freeze-thaw cycles or the type of failure mode was observed on delamination length.

6.3 Recommendations

1. Freeze-Thaw (F.T.) cycles influence the behavior of reinforced concrete beams with glued-on Carbon Fiber Reinforced Plastic (CFRP) laminates. According to this study, with the Tonen system a maximum decrease of 29% of flexural capacity could be expected after 200 FT and 38% after 300 F.T. cycles. With the Sika system, the maximum decrease observed was of 13% after 200 F.T. cycles. It should be pointed out that the influence of the Freeze-Thaw cycles may also affects the concrete strength, but its effect cannot be easily observed from testing a reinforced concrete beam in bending; it is possible that this dual effect explains the decrease in strength. Unless some additional tests are carried out, as a first design approximation, it is recommended that a reduction of 40% in horizontal shear strength be taken to account for freeze-thaw exposure.

2. The value of the horizontal interfacial shear strength can be taken conservatively as $0.17\sqrt{f'_c}$ for both strengthening systems. Preliminary analyses indicate that this value may be close to 1.70 MPa for Tonen system and 2.64 MPa for the Sika system, considering the effect of the different strengthening level provided by the two systems. Further study of the interface bond behavior is needed in order to refine this value.

3. The minimum value of the development length (or anchorage) of the CFRP laminate should be based on the value of $0.17\sqrt{f'_c}$. This value could be modified by results from further investigations. It is recommended that the bonded length of the CFRP should be as long as possible in order to avoid an interfacial bond failure and to have a more efficient use of the CFRP sheet strength.

4. Since delamination seems to be controlled by the interface bond between the CFRP laminate and the concrete, which is also controlled by the concrete strength, it is strongly recommended to insure very good surface preparation before application of the strengthening system.

6.4 Correlation with Shear Tests

Average interlaminar shear stresses at failure measured in the beams tested for shear strengthening were $0.06\sqrt{f'_c}$ and $0.10\sqrt{f'_c}$ for the Tonen and Sika system, respectively. Interlaminar shear stresses along the tensile face of the beam calculated at failure for the freeze-thaw test beams were significantly higher, exceeding $0.19\sqrt{f'_c}$. Although the reason for this difference needs to be ascertained in future tests, it is suggested that it could arise from scale effects, due to the fact that the freeze-thaw beams were much smaller that the beams for shear strengthening. Since interlaminar shear failure within the concrete is a brittle fracture failure, a fracture mechanics analysis may provide a rational explanation for this observation.

7. TECHNICAL SPECIFICATIONS (VOLUME 7)

7.1 Summary

These specifications provides sections on description of the technology, materials used including pertinent data for commercial CFRP systems, comparison of commercial adhesives, equipment needed, and execution. For the execution section, details related to assessment of existing conditions, surface preparation, mixing of adhesive, application to the structure, comparison between different commercial systems, and safety precautions are also provided. These specifications are derived by the experience gained during the course of this project and information extracted from different commercial and research sources.

In additions two appendices are included. One dealing with special provisions for using the SIKA CARBODUR (CFRP) laminates for structural strengthening, and the other dealing with special provisions for using the MBRACE (CFRP) composite strengthening system. These special provisions were essentially obtained from the respective suppliers of each system. In case of use of a particular CFRP system, the application procedure provided by the system supplier should be followed.

The successful application and use of these technical specifications is sole responsibility of the user and is dependent on the application of sound judgment by qualified professional engineer with a thorough understanding of concrete behavior and structural mechanics.

8. DESIGN GUIDELINES

A number of design parameters were investigated in this project. However, in many cases only one specimen was tested and results with only one specimen may not be definitely conclusive. The design guidelines suggested next are based on the observed results and the experience gained from the project.

1. Strengthening RC beams in bending or shear using adhesively bonded CFRP sheets is a feasible and reliable technology. However, strengthening leads to a reduction in ductility as evidenced by a reduction in deflection at failure.

2. Strengthening should be limited to balance a portion of live load only. Should the strengthening system fail, the structure under repair should be analyzed (or designed) to resist the dead load and the remaining portion of live load.

3. Although numerous factors can affect the extent to which a reinforced concrete beam can be strengthened for bending using adhesively bonded CFRP laminates, it seems safe to design for increments of bending strength not exceeding about 20% of the nominal bending resistance of the beam calculated assuming a reinforcement ratio equal to ρ_{max}, where ρ_{max} is the maximum reinforcement ratio defined in the ACI Building Code or the AASHTO Specification. Also, in order to comply with the code, it is necessary to keep the total reinforcement ratio or reinforcement index below their respective maximum value recommended in the code.

4. A smaller concrete cover is generally better than a larger one.

5. A repaired concrete cover prior to application of the CFRP laminates is likely to fail at the interface between the old concrete substrate and the new cover. However, the failure will be more ductile than with a virgin cover.

6. U-shaped anchorages are not necessary at the ends of the CFRP laminates. Extending the laminate over its development length should be sufficient.

7. In analyzing or designing a strengthened RC. beam, the design criteria should include not only equilibrium, strain compatibility, and stress-strain relations of component materials, but also criteria related to the interlaminar shear resistance of the concrete both in the direction of bending and shear. There is need to determine the resistance of concrete in shear when subjected simultaneously to tension or compression.

8. Because of possible scale effects and the brittle nature of failure in shear, it is recommended to design on the basis of a concrete interlaminar shear strength not exceeding $0.10\sqrt{f'_c}$ where f'_c is in MPa.

9. Fatigue tests at temperature of -29 °C showed that the CFRP and epoxy adhesive system remain as effective and reliable as at normal temperatures.

10. Freeze-thaw tests affects mostly the interlaminar shear resistance of the concrete substrate leading to failures modes by interlaminar shear similar to those observed for the control beams.

12. For design it is recommended to reduce the code recommended interlaminar shear resistance of concrete by up to 40% when full cycles of freeze-thaw exposure are expected. The value recommended in 8 above meets this recommendation.

13. For design, it is recommended that the development length of the bonded sheet be calculated based on the interlaminar shear resistance of the concrete to which it will be bonded (see 8 above). As a measure of safety, the full strength of the sheet can be used in computing the development length. However, the development length can also be calculated on the basis of the maximum expected tensile load to be resisted by the bonded sheet, as obtained from strain compatibility analysis.

9. CONCLUDING REMARK

The reader is strongly urged to refer to the details of this investigation as described in Volumes 2 to 7 prior to embarking on an important strengthening project dealing with this new technology.

At time of completion of this project, ACI Committee 440, FRP Reinforcement, was completing two documents of interest to this project: one dealing with design issues, and the other dealing with specifications related to the use of the adhesive bonded laminate technique for repair and strengthening of concrete structures. These references are also highly recommended.