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Durability Evaluation of Carbon Fiber-Reinforced Polymer Strengthened Concrete Beams: Experimental Study and Design

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This paper deals with the durability of the reinforced concrete (RC) beams externally strengthened with carbon fiber-reinforced polymer (CFRP) plates and fabrics under adverse environmental conditions such as 100% humidity, saltwater, alkali solution, freeze-thaw, thermal expansion, dry-heat, and repeated load cycles. The deflections, strains, failure loads, and failure modes of strengthened beams exposed to different independent environmental conditions and repeated load cycles are presented. To determine the design strength of CFRP-strengthened beams exposed to long-term environmental conditions, strength reduction factors associated with various independent environmental conditions are proposed. In addition, the failure modes and physical changes of the beams exposed to various independent environmental conditions were also examined. It is concluded that the long-term exposure to humidity is the most detrimental factor to the bond strength between CFRP plates and fabrics and RC beams. Beams strengthened with CFRP plates and exposed to 10,000 hours of 100% humidity (at 38 ± 2 °C) experienced an average of 33% reduction in their strength. The onset of delamination was the primary mode of failure for all of the test beams. Finally, a durability-based design approach is presented. The design approach appropriately demonstrates the evaluation of nominal and design moment strengths of the beam strengthened with CFRP plates and exposed to a 100% humidity condition.

Keywords: beams; concrete; durability; fiber.

INTRODUCTION

Today, carbon fiber-reinforced polymer (CFRP) materials are being used worldwide for the retrofitting and repair of deficient and old infrastructures such as bridges and buildings. Over the years, these structures have suffered severe strength and stiffness deterioration due to aggressive environmental conditions such as humidity, saltwater, and alkali solutions. Advanced fibrous composite materials such as CFRP can eliminate the problem of corrosion and substantially increase the strength and stiffness of the beams internally reinforced with CFRP bars. In the case of reinforced concrete (RC) beams externally strengthened with CFRP plates and fabrics and exposed to aggressive environmental conditions, however, the bond between the CFRP plate and the surface of the RC beam significantly affects the strength of externally reinforced RC beams. Thus, it is essential to investigate the overall response of the RC beams externally strengthened with CFRP plates and fabrics and exposed to different environmental conditions.

From the experimental investigations of David and Neuner[1] and Karbhari and Engineer[2] on the effects of environmental conditions on the response of externally strengthened RC beams, it is concluded that the long-term exposure to humidity may cause a significant decrease in the load-carrying capacity of the RC beams. In addition, the study of Karbhari and Engineer[2] also revealed that even short-term exposure to humidity may cause significant degradation of the CFRP strengthening system depending on the compatibility between the fiber and resin and the resin characteristics. Similarly, Juska et al.[3] analyzed the data related to thermal exposure and freezing-and-thawing conditioning and concluded that elevated temperature and freezing-and-thawing cycles have significant effects on the fiber-reinforced polymer (FRP) composite systems. Benmokrane et al.[4] studied the effects of alkaline solution on the FRP composites and confirmed that alkaline environment may cause degradation of both the stiffness and strength of various FRP composites.

Leung, Balendran, and Lim[5] investigated the flexural capacity of steel and CFRP-strengthened concrete beams exposed to different environmental conditions. They concluded that strengthening with CFRP plates causes greater strength enhancement than strengthening with steel plates. They also observed that exposure to water for long periods caused a reduction of the load-carrying capacity as well as an increase in midspan deflection. Zheng and Morgan[6] investigated the synergistic thermal-moisture damage mechanisms of epoxies and their carbon fiber composites. Reverse thermal effects were investigated after measuring the weight change of the epoxy resins and their carbon fiber composites when immersed in the distilled water at temperatures ranging between 33 and 170 °F (0.5 and 80 °C). It was determined that a critical temperature regime exists above which the resin has the ability to absorb greater amounts of water. Karbhari, Engineer, and Eckel[7] modified the peel test method for assessing changes in bonding between glass fiber-reinforced polymer (GFRP) and CFRP composites and concrete. They concluded that the exposure of GFRP and CFRP composites to aqueous solutions had a significantly deleterious effect, indicating that most of the degradation was at the level of the epoxy layer between composite and concrete. Chin et al.[8] studied the environmental effects on composite matrix resins used in construction. Specimens were exposed to an alkaline solution combined with a high temperature of 194 °F (90 °C) for approximately 10 weeks. They observed significant degradation in specimens and changes in glass transition temperature and tensile strength.

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In this paper, responses of RC beams externally strengthened with CFRP plates and fabrics and exposed to various independent environmental conditions such as humidity, dry-heat, alkaline and saltwater solutions, thermal expansion, freezing-and-thawing conditionings, and repeated load cycles are presented and discussed. In addition, a durability-based design approach[9] is presented through a design example in Appendix A.*

EXPERIMENTAL PROGRAMS AND CONSTRUCTION DETAILS

As shown in Table 1, a total of 78 RC beams consisting of two unstrengthened beams, four baseline beams (two beams strengthened with CFRP plates and two beams strengthened with CFRP fabrics but not exposed to environmental conditions), and 72 strengthened beams exposed to environmental conditions and repeated load cycles were tested.

All 78 RC beams had a rectangular cross section (152 x 254 mm [6 x 10 in.]) and were 2743 mm (108 in.) long. Concrete mixture proportions having a characteristic cylinder strength of 31 MPa (4.5 ksi) after 28 days were used. Figure 1 shows the longitudinal and cross-sectional details of test beams. The flexural reinforcement consisted of two No. 5 (15.9 mm diameter) steel bars at the bottom and two No. 3 (9.5 mm diameter) steel bars at the top of the beams. Shear reinforcement was provided in the form of two-legged rectangular-shaped (102 x 203 mm [4 x 8 in.]) stirrups with standard hooks. Stirrups were made of No. 3 steel bars. The center-to-center spacing of stirrups was 102 mm (4 in.). All reinforcing steel bars were of Grade 60 having a characteristic strength of 414 MPa (60 ksi). Beams were cast using metal forms.

It should be noted that the supplier installed the CFRP plates, while the installation of CFRP fabrics on the RC beams was performed at the Structural Testing Center at Lawrence Technological University. The installation procedure for both the CFRP fabrics and CFRP plates was the same except that the number of layers of CFRP plates was one, while the CFRP fabrics were bonded in two layers. In addition, structural epoxy was used for bonding the CFRP plates, while saturating epoxy was used for bonding CFRP fabrics. This configuration allowed maintaining equal nominal load carrying capacities for both types of strengthened beams. The following section explains the procedure for the installation of CFRP fabrics.

CFRP fabrics installation procedure

CFRP fabrics[10] were bonded to the test beams as per the instructions provided by the manufacturer. All irregularities found on the concrete surface of the beam were removed using a hand grinder and a masonry-grinding wheel. The surface was sand blasted to ensure proper bonding of the CFRP fabrics. Saturating epoxy supplied by the same company was used to fill voids and low spots on the surfaces of the beams and was allowed to cure for 24 h.

Two layers of fabric (refer to Fig. 1(c)) of 0.2 mm (0.007 in.) thickness, 152 mm (6 in.) width, and 2235 mm (88 in.) length were used for the strengthening of each beam. The first layer of the CFRP fabric was bonded to the

*The Appendix is available in xerographic or similar form from ACI headquarters, where it will be kept permanently on file, at a charge equal to the cost of reproduction plus handling at time of request.

Table 1—Details of tested beams after exposure to environmental conditions and repeated load ranges

Specific environmental condition	Hours of exposure	No. of test beams strengthened with CFRP plates and fabrics		Designated repeated load range	Magnitude of repeated load range (% of ultimate strength of baseline beams*)	Test beams strengthened with CFRP plates and fabrics	
		CFRP plate	CFRP fabric			CFRP plate	CFRP fabric
100% humidity	1000	2	2	R15	15	2	2
	3000	2	2				
	10,000	2	2				
Dry heat	1000	2	2	R25	25	2	2
	3000	2	2				
	10,000	2	2				
Saltwater solution	1000	2	2	R40	40	2	2
	3000	2	2				
	10,000	2	2				
Alkaline solution	1000	2	2	—	—	—	—
	3000	2	2	—	—	—	—
	10,000	2	2	—	—	—	—
Freezing-and-thawing	350 cycles	2	2	—	—	—	—
	700 cycles	2	2	—	—	—	—
Thermal expansion	35 cycles	2	2	—	—	—	—
Baseline beams*	N/A†	2	2	—	—	—	—
Unstrengthened beams	N/A	2	2	—	—	—	—

*Baseline beams refers to beams strengthened with CFRP plates and fabrics without exposure to any environmental conditions/repeated loads.
†N/A refers to not applicable.
Note: total number of test beams = 78.

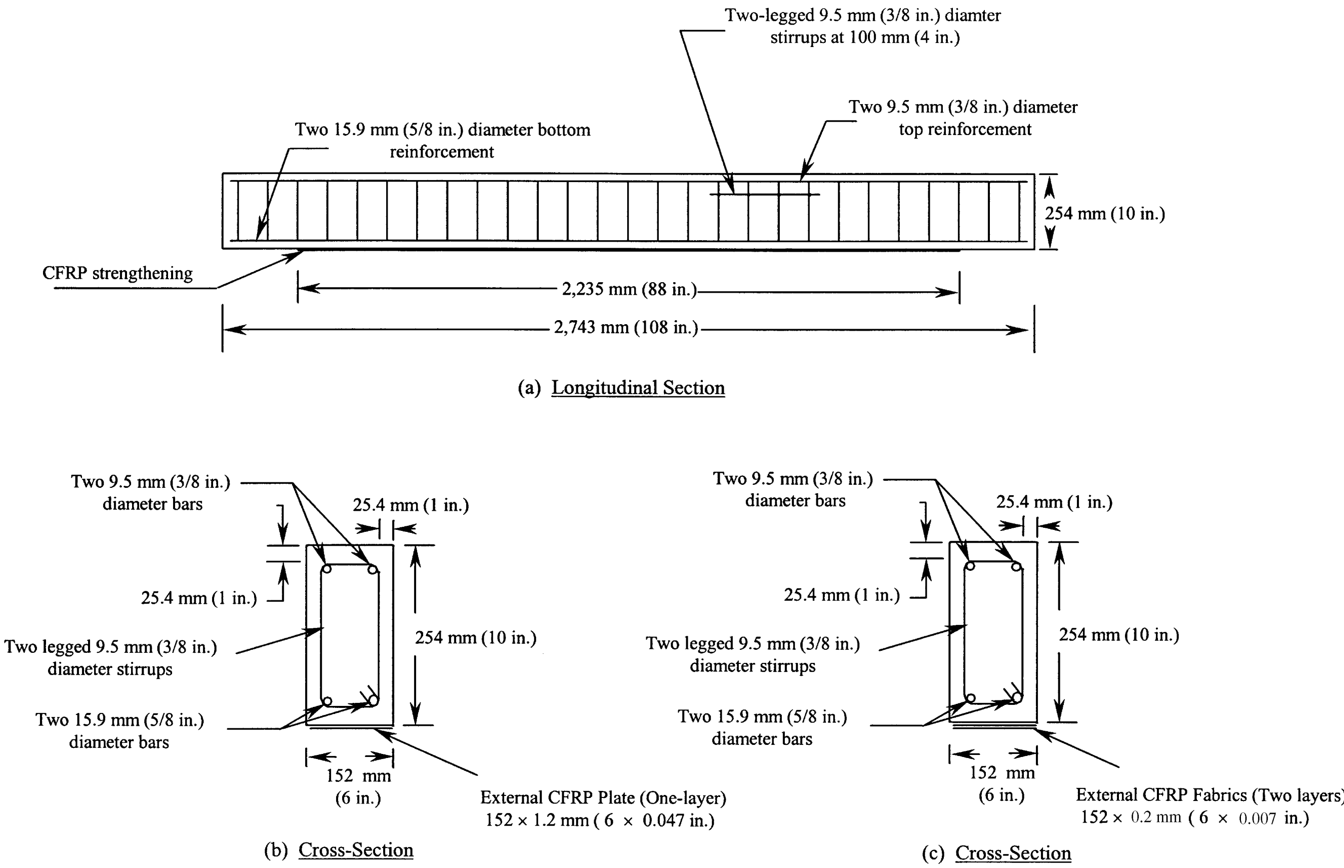

Fig. 1—Longitudinal and cross-sectional details of test beams.

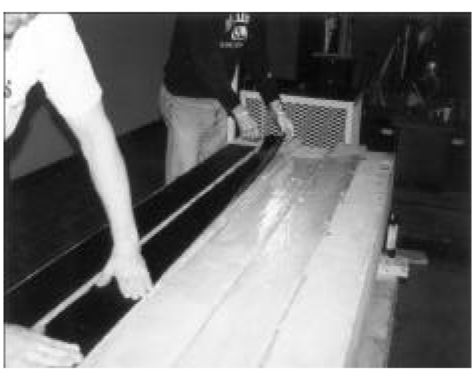

Fig. 2—Installation of first layer of CFRP fabric.

Table 2—Mechanical properties of CFRP strengthening materials[10]

Property	CFRP plates	CFRP fabrics
Width, mm (in.)	76.2 (3.0)	152 (6.0)
Thickness, mm (in.)	1.2 (0.047)	0.2 (0.007)
Average modulus of elasticity, GPa (ksi)	138 (20,000)	227 (33,000)
Average ultimate strain, %	1.5	1.8
Average ultimate tensile strength, MPa (ksi)	2070 (300)	2758 (400)

prepared surface of the concrete as shown in Fig. 2. Subsequently, the second layer of CFRP fabric was bonded over the first layer using the same saturating epoxy. Hand rollers were used to properly bond the fabrics together and to remove any trapped air between them. Material properties of CFRP fabrics and CFRP plates, as provided by the manufacturer, are presented in Table 2, while properties of structural epoxy and saturating epoxy used for bonding the CFRP plate and CFRP fabric are presented in Table 3.

ENVIRONMENTAL CONDITIONINGS

Three stainless steel tanks were designed and constructed for 100% humidity, alkaline, and saltwater solution conditionings. Each tank was designed to accommodate 12 beams arranged in three rows of four beams each. Each tank was 3.05 m (10 ft) long, 1.22 m (4 ft) wide, and 1.22 m (4 ft) deep. Each row consisted of four beams: two beams strengthened with CFRP plates and two beams strengthened with CFRP fabrics. Three rows of the beams were spaced apart using three 102 x 102 mm (4 x 4 in.) treated lumber blocks at each end of the tank (Fig. 3) to ensure adequate soaking. Each tank had: a) a heating blanket placed under the bottom surface to maintain the temperature of solution as per ASTM standards; b) two pumps positioned at opposing corners of the tank to allow adequate water circulation; and c) thermocouples to continuously monitor the temperature inside the tanks. The top, middle, and bottom rows of the beams were removed after 1000, 3000, and 10,000 h of a particular environmental conditioning, respectively. It should be noted that the beams

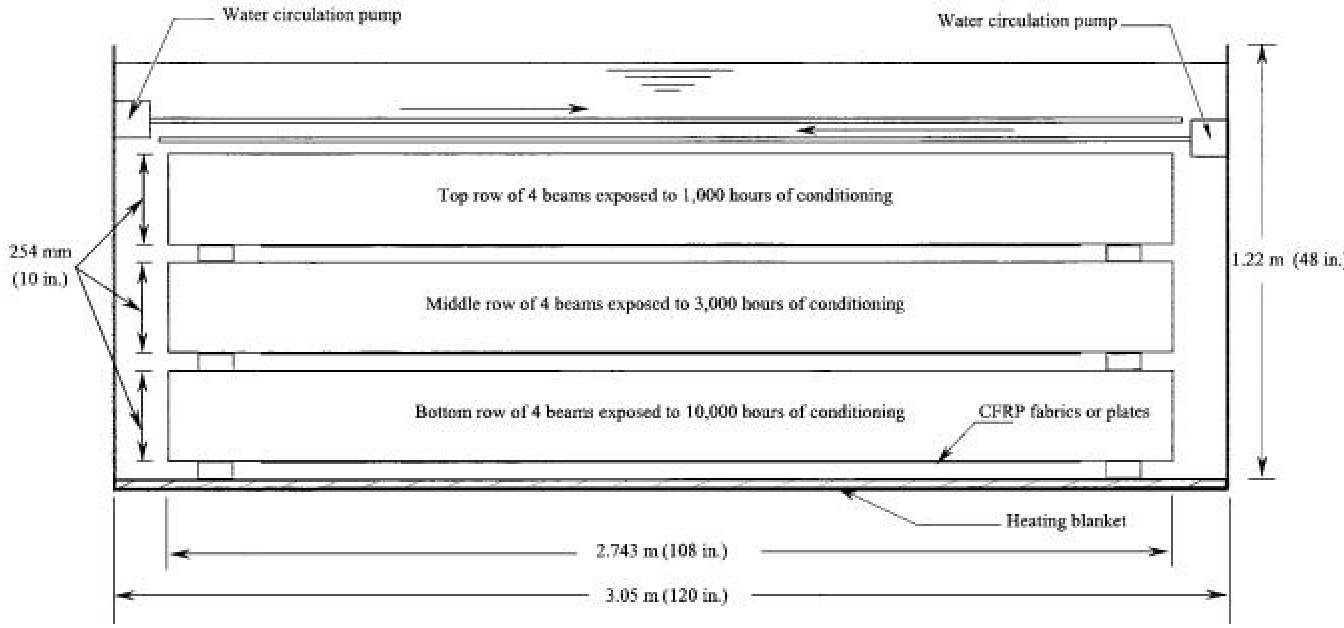

Fig. 3—Schematic of tanks used for humidity, saltwater, and alkaline solution exposures.

Table 3—Typical properties for epoxies[10]

Properties	Structural epoxy	Saturating epoxy
Tensile strength, MPa (ksi)	60.7 (8.8)	62 to 75.8 (9 to 11)
Adhesion strength, MPa (psi)	>2 (290)	>2 (290)
Flexural strength, MPa (ksi)	100 (14.5)	103.4 to 131 (15 to 19)
Flexural modulus, GPa (ksi)	2.14 (310)	2.41 (350)
Glass transition temperature T_g, °F (°C)	140 (60)	140 (60)

removed from the tanks after 1000, 3000, and 10,000 h of exposure to environmental conditioning were left to dry and the change in the weight of beams was measured.

The beams were transported to the Structural Testing Center and were instrumented for the ultimate load test. The 100% humidity condition at 38 ± 2 °C (100 ± 3 °F) was maintained in the tank as per ASTM standards,[11] while the alkaline and saltwater solutions at 23 ± 2 °C (73 ± 3 °F) were prepared as per the procedures of ASTM C 581[12] and ASTM D 1141,[13] respectively. Figure 4 shows the beams exposed to 10,000 h of saltwater solutions. It should be noted that all environmental conditionings were based on ASTM standards as per the requirement of the funding agencies.

To examine the effect of dry-heat conditioning on the beams strengthened with CFRP plates, a specially designed and manufactured dry-heat chamber was used to meet the ASTM D 3045 standard.[14] The dry-heat chamber was 3.4 m (11 ft) long, 1.5 m (5 ft) wide, and 2.1 m (7 ft) deep. The beams were arranged in three rows as in the case of 100% humidity conditioning (Fig. 3). The chamber was heated to 60 °C (140 °F), and the top, middle, and bottom rows of beams were kept under the steady heat for 1000, 3000, and10,000 h, respectively. Figure 5 shows the bottom row of four beams exposed to 10,000 h of dry-heat conditioning. To determine the performance of beams under a freezing-and-

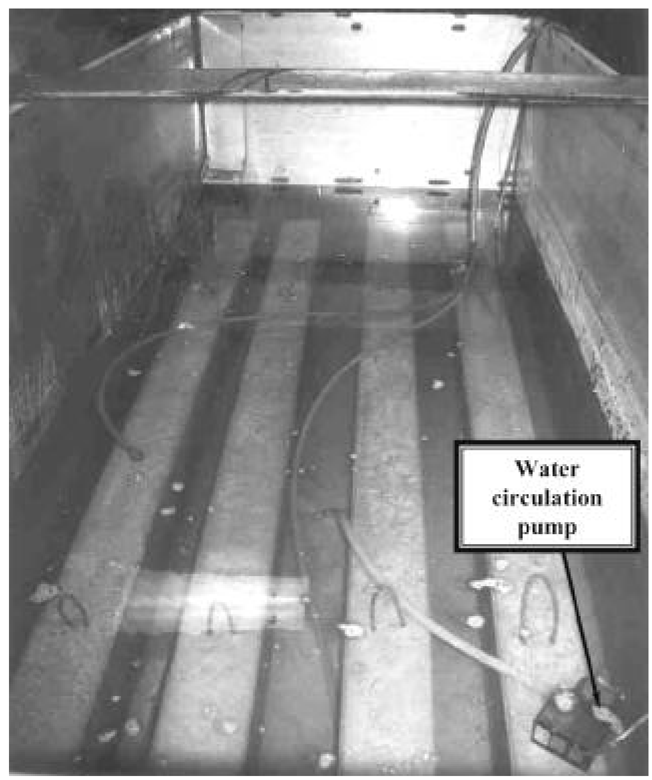

Fig. 4—Bottom row of four beams exposed to saltwater for 10,000 h.

thawing environment, beams were exposed to 350 and 700 freezing-and-thawing test cycles in an environmental chamber designed and manufactured to meet the ASTM C 666B[15] requirements. The nominal freezing-and-thawing cycle consisted of first lowering the temperature of the beam from 4 to –17.8 °C (40 to 0 °F) and then raising it from –17.8 to 4 °C (0 to 40 °F). Air was used to freeze the beams, while water was used to thaw them. Each freezing-and-thawing

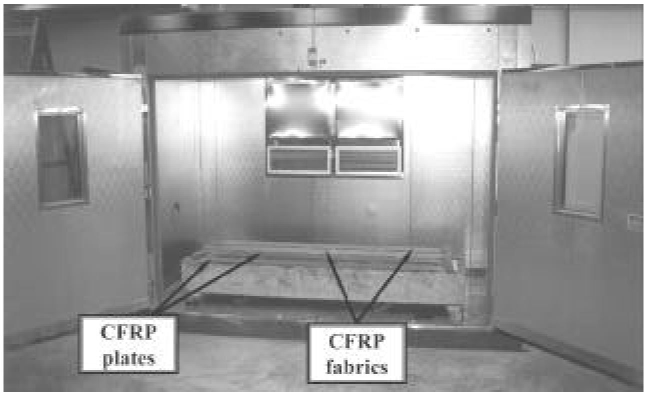

Fig. 5—Bottom row of four beams exposed to 10,000 h of dry heat.

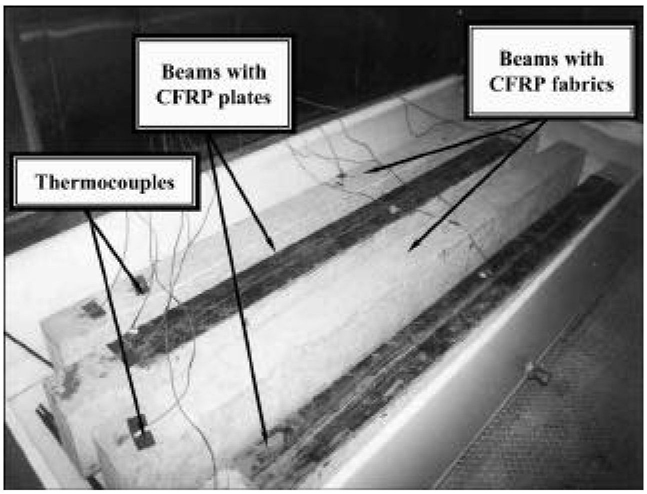

Fig. 6—Arrangement for thermal expansion test.

cycle took 4 h.[16] The chamber used for freezing-and-thawing conditioning was 6.1 m (20 ft) long, 3.6 m (12 ft) wide, and 2.7 m (9 ft) deep. To examine the effect of thermal expansion on the CFRP strengthened beams, the same freezing-and-thawing conditioning chamber was used as the heat chamber (Fig. 6) for thermal expansion. The chamber was designed for the maximum temperature of 75.5 °C (168 °F) and maximum humidity of 100%. Each thermal expansion test cycle consisted of raising the temperature of the beam to 48.9 ± 1.5 °C (120 ± 2 °F) and then cooling it down to 26.7 ± 1.5 °C (80 ± 2 °F). The total duration of each thermal expansion test cycle was 5 h. All the beams were exposed to 35 thermal expansion test cycles. As in the case of beams exposed to 100% humidity, alkaline, and saltwater solutions, beams exposed to dry heat, freezing-and-thawing, and thermal expansion were removed from the chambers and were weighed before transporting to the Structural Testing Center for the ultimate load test. The thermal expansion test was conducted as per the requirements of ASTM C 531.[17]

ULTIMATE LOAD TEST

To determine deflections, strains, and the ultimate failure loads of the beams strengthened with CFRP plates and fabrics with and without exposure to the different environmental conditions and repeated load cycles, beams were first instrumented with strain gages (Fig. 7) and linear variable

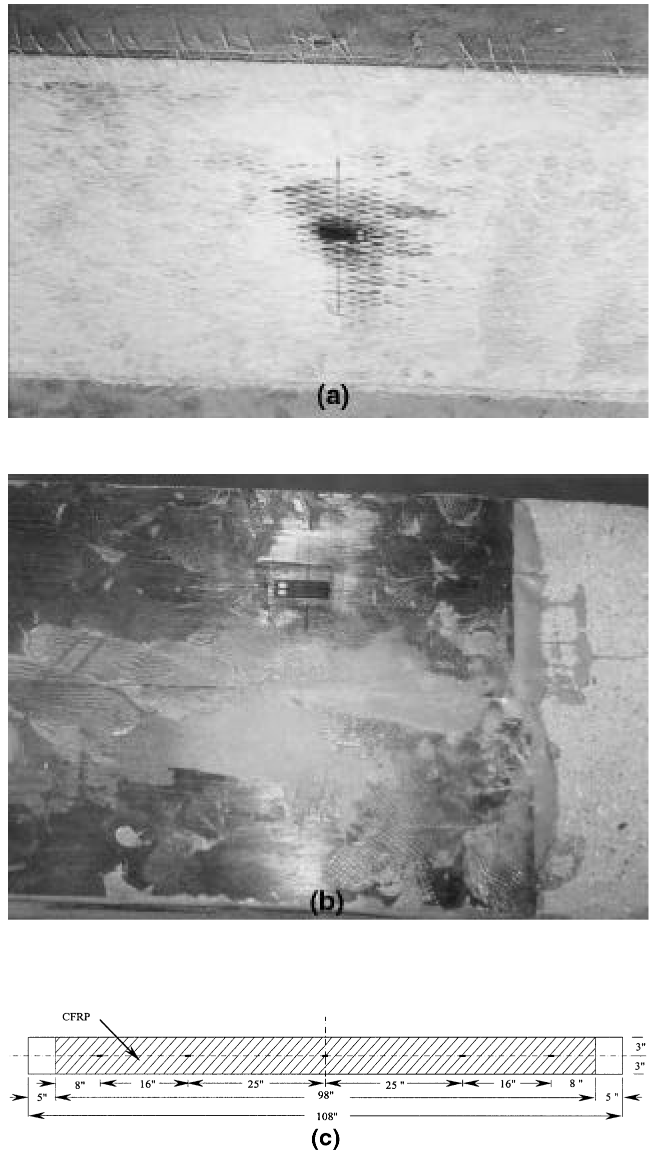

Fig. 7—Instrumentation of strain gauges along span of strengthened beam: (a) strain gauge installed on CFRP fabric; (b) strain gage installed on CFRP plate; and (c) bottom view of CFRP plate and fabric.

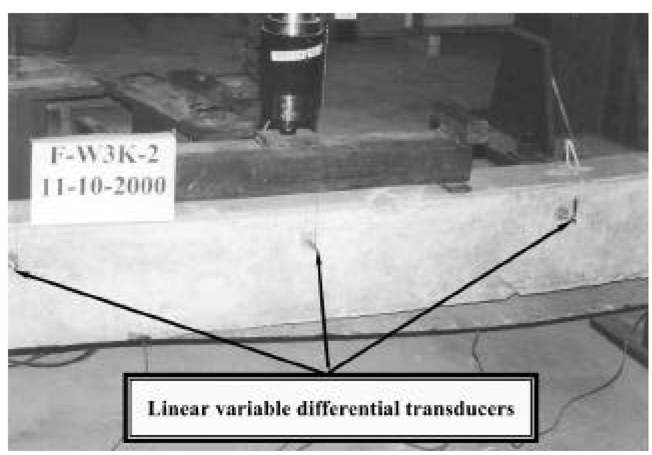

Fig. 8—Four-point ultimate and repeated load systems with linear variable differential transducers.

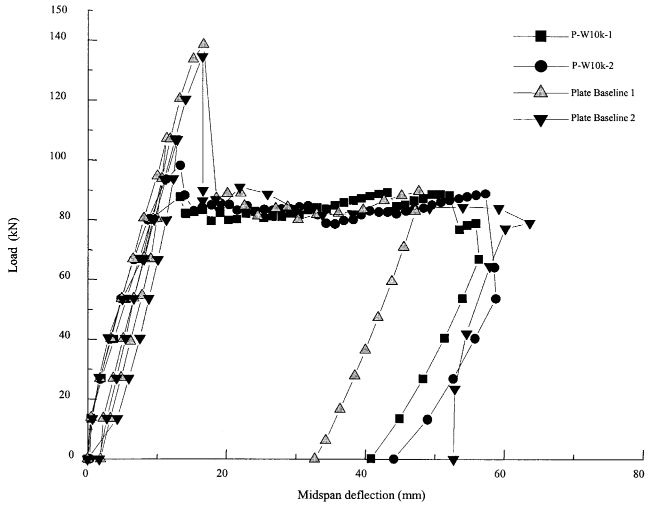

Fig. 9—Load-versus-deflection relationships for beam strengthened with CFRP plates exposed to 10,000 h of 100% humidity at 100 °F.

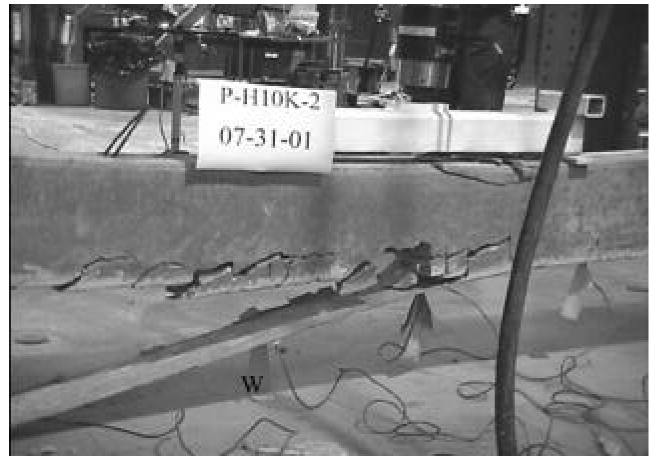

Fig. 10—Closeup of ultimate failure of beam strengthened with CFRP plate after 10,000 h of exposure to 100% humidity.

Fig. 11—Closeup of ultimate failure of beam strengthened with CFRP fabrics after 10,000 h of exposure to dry-heat condition.

displacement transducers (Fig. 8). The instrumented CFRP strengthened beams were subjected to a four-point loading system (as shown in Fig. 8) to predict the deflection, strain, failure loads, and failure modes of the beams. The center-to-center distance between supports was 2.54 m (100 in.). The length of the centrally placed loading beam (Fig. 8) was 0.813 m (32 in.), keeping the distance of the end of the loading beam from the nearest beam support equal to 0.864 m (34 in.). Prior to the ultimate failure, beams were loaded and unloaded in two stages. In the first stage, beams were loaded up to 53.4 kN (12 kips) and unloaded to zero load, while in the second stage, beams were reloaded to 106.8 kN (24 kips) and then unloaded to zero load. Finally, all beams were loaded to failure. It should be noted that the loading was applied in the displacement mode. The rates of loading and unloading were 0.10 and 0.25 mm/s (0.004 and 0.01 in./s), respectively. Deflections and strains were measured using a test control software package at 13.4 kN (3 kips) increments. Details of construction, instrumentation, and test procedure can be found elsewhere.[9,16]

RESULTS AND DISCUSSION

Although the exposure of test beams to different environmental conditions resulted in similar load-deflection and load-strain responses, the most significant change in the response of beams was observed in the case of beams strengthened with CFRP plates and exposed to 10,000 h of 100% humidity condition. Figure 9 shows the load-deflection response of plate baseline beams (beams without environmental exposure) and the two beams (P-W10k-1 and P-W10k-2) strengthened with CFRP plates and exposed to 10,000 h of 100% humidity. It is shown that the load-carrying capacity of beams exposed to 100% humidity is significantly reduced (approximately 33% reduction) in comparison to that of corresponding baseline beams (that is, CFRP-strengthened beams without environmental exposure). For a specific load before the ultimate failure, however, there is no significant difference in the deflection of baseline beams and that of beams exposed to 100% humidity condition. As shown in Fig. 9, baseline beams and beams exposed to humidity conditioning show a sudden drop of the load followed by a large deflection at a constant load before their complete collapse. This is attributed to the failure of the beams by the onset of delamination of the CFRP plates at a load close to the observed ultimate failure load of the beams. Figure 10 shows the ultimate failure of the beam strengthened with CFRP plates after 10,000 h of exposure to the humidity condition. A similar failure mode was observed for the beams strengthened with CFRP fabrics (Fig. 11). The onset of delamination (Fig. 10 and 11) was immediately followed by crushing the concrete. It should be noted that all of the strengthened beams with or without exposure to environmental conditions failed due to debonding or onset of delamination (shear-tension failure) of the CFRP plates and fabrics. Thus, debonding and onset of delamination are the actual modes of failure of CFRP strengthened beams and govern the load-carrying capacity of these beams. The onset of delamination/debonding of CFRP plates and fabrics is primarily dependent on the bond between the concrete surface and CFRP plates and fabrics through structural/saturating epoxy. As shown in Fig. 9, the decrease in the shearing strength of structural epoxy

Table 4—Details of failure loads, failure modes, and corresponding deflections and strains of beams strengthened with CFRP plates and fabrics

Test	Hours of exposure to environmental conditions	Average failure load,* kN (kips)		Average deflection, mm (in.)		Average strain $\times 10^{-6}$		Failure modes
		Plate	Fabric	Plate	Fabric	Plate	Fabric	
100% humidity	1000	148.2 (33.3)	124.2 (27.9)	18.0 (0.71)	19.8 (0.78)	3761	5462	All strengthened beams failed due to onset of delamination or debonding of CFRP fabrics and plates
	3000	112.6 (25.3)	125.9 (28.3)	15.7 (0.62)	19.3 (0.76)	3641	4998	
	10,000	93 (20.9)	120.6 (27.1)	13.5 (0.53)	20.3 (0.80)	1834	4926	
Dry heat	1000	126.8 (28.5)	135.7 (30.5)	14.7 (0.58)	21.8 (0.86)	6281	3831	
	3000	119.3 (26.8)	137.1 (30.8)	17.0 (0.67)	22.9 (0.9)	4944	3718	
	10,000	125.9 (28.3)	137.5 (30.9)	16.5 (0.65)	25.4 (1.0)	6126	3438	
Saltwater solution	1000	144.6 (32.5)	126.4 (28.4)	17.0 (0.67)	21.6 (0.85)	4163	5741	
	3000	150.0 (33.7)	126.4 (28.4)	19.1 (0.75)	19.1 (0.75)	3867	4453	
	10,000	129.9 (29.2)	123.7 (27.8)	17.3 (0.68)	21.3 (0.84)	3447	5180	
Alkali solution	1000	136.6 (30.7)	133.1 (29.9)	16.0 (0.63)	21.6 (0.85)	4229	6173	
	3000	149.1 (33.5)	125.9 (28.3)	19.1 (0.75)	19.6 (0.77)	4288	4900	
	10,000	139.7 (31.4)	120.2 (27.0)	20.6 (0.81)	22.1 (0.87)	4478	5665	
Freezing-and-thawing	350 cycles	119.7 (26.9)	125.0 (28.1)	16.0 (0.63)	19.1 (0.75)	3500	4900	
	700 cycles	123.7 (27.8)	116.1 (26.1)	18.5 (0.73)	25.4 (1.0)	3400	5000	
Thermal expansion	35 cycles	115.3 (25.9)	134.8 (30.3)	22.9 (0.90)	19.1 (0.75)	3400	5000	
Baseline	—	136.6 (30.7)	133.5 (30.0)	16.0 (0.63)	22.9 (0.90)	3988	6150	

*Failure load of unstrengthened reinforced concrete beam was 85 kN (19.3 kips). Average test results are based on two test beams for each environmental conditioning.

Table 5—CFRP strength reduction factors ψ for different environmental conditions

Environmental condition	CFRP plates	CFRP fabrics	Environmental strength reduction factors for CFRP[18]		
100% humidity	0.70	0.90	Interior exposure	Exterior exposure (bridges, piers, unenclosed parking garages)	Aggressive environmental conditions (chemical plants and waste water treatment plants)
Dry heat	0.90	1.00	0.95	0.85	0.85
Alkalinity	1.00	0.90	—	—	—
Freezing-and-thawing	0.90	0.85	—	—	—
Salinity	0.95	0.90	—	—	—

Table 6—Ultimate failure loads of beams subjected to repeated load range

Beam	Average ultimate failure load,* kN (kips)
Unstrengthened	85.9 (19.3)
Plate baseline	138.4 (31.1)
Beam P-R15	126.4 (28.4)
Beam P-R25	129.9 (29.2)
Beam P-R40	146.9 (33.0)
Fabric baseline	129.5 (29.1)
Beam F-R15	125.9 (28.3)
Beam F-R25	125.9 (28.3)
Beam F-R40	130.4 (29.3)

*Average ultimate failure loads are based on two test beams for each repeated load range.

due to continuous exposure to a 100% humidity condition at 38 °C (100 °F) led to significantly (approximately 33%) reduced load-carrying capacity caused due to onset of delamination. This result confirms the results obtained by Leung, Balendran, and Lim[5] and Zheng and Morgan.[6]

Details of the average failure loads and corresponding deflections and strains and failure modes of the beam exposed to different environmental conditions for different durations are presented in Table 4. The average values of the test results (Table 4) are based on two test beams for each environmental condition of specific duration. It is observed that external strengthening of RC beams using CFRP plates and fabrics increased the strength of the beam by approximately 59 and 55%, respectively. It is also observed that unlike in the case of 100% humidity, the dry-heat condition does not have significant effect on the failure loads of beams strengthened with CFRP plates, whereas failure loads of beams strengthened with CFRP fabrics increased due to dry-heat conditioning. The slightly increased failure loads of beams strengthened with CFRP fabrics under the dry-heat condition may be attributed to the fact that dry-heat conditioning temperature was close to that of the glass transition temperature T_g of saturating epoxy used for bonding the CFRP fabrics with the concrete surface, which in turn led to the development of improved bond strength between fabrics and concrete surface. The improved bond strength of saturating epoxy caused delayed onset of delamination of the CFRP fabrics in comparison to that for structural epoxy used for bonding the CFRP plates. The longer duration of humidity reduced the shearing strength of structural epoxy, leading to the early onset of delamination of CFRP plates. It is noted that saltwater and alkaline solutions are shown to improve the load-carrying capacity of beams strengthened with CFRP plates, especially for short-term exposure (that is, 3000 h). The humidity and saltwater solution decrease the load-carrying capacity of beams strengthened with CFRP fabrics; however, duration of exposure to humidity and saltwater solution has no significant effect on failure loads of these beams unlike the beams strengthened with CFRP plates.

The 35 thermal expansion test cycles (Table 4) reduced the failure loads of beams strengthened with CFRP plates by approximately 15%, while thermal expansion test cycles have no significant effect on the failure loads of beams strengthened with CFRP fabrics. Similarly, it is observed that 350 and 700 freezing-and-thawing cycles decreased the load-carrying capacity of beams strengthened with CFRP plates by approximately 3.3 and 9.5%, respectively. The corresponding reduction in failure loads of beams strengthened with CFRP fabrics due to 350 and 700 freezing-and-thawing cycles are 6 and 13%, respectively.

From Table 4, it is also observed that deflection corresponding to failure loads of beams strengthened with CFRP fabrics are larger than that for beams strengthened with CFRP plates. Similar observations are made for the strains at failure loads, except in the case of dry-heat conditioning, where beams strengthened with CFRP fabrics experienced lower strain than that for the beams strengthened with CFRP plates. This condition is due to improved bond characteristics of saturating epoxy used in the case of beams strengthened with CFRP fabrics compared with structural epoxy used for the beams strengthened with CFRP plates. It should be noted that the magnitude of the strain developed in the CFRP plate and fabrics governs the failure load of the beam, and hence the onset of delamination/debonding. The onset of delamination of CFRP plates and fabrics emphasizes the importance of development of adequate bond strength between CFRP plates and fabrics with concrete surface, which primarily depends on the physical and mechanical characteristics of the bonding epoxy.

Based on the experimental results of beams strengthened with CFRP plates and fabrics and exposed to various independent environmental conditions, strength reduction factors associated with 100% humidity, dry heat, alkaline solution, freezing-and-thawing condition, and saltwater solution were evaluated and are presented in Table 5 along with the environmental strength reduction factors proposed in ACI 440.2R-02.[18] Each strength reduction factor is based on the ratio of the ultimate load of the strengthened beam exposed to independent environmental condition to that of baseline beam. It is observed that strength reduction factors of the present study are close to those proposed in ACI 440.2R-02 (Table 5) with an average value of 0.9 considering all environmental conditions for CFRP plates and fabrics. Thus, the strength reduction factors obtained from the present study confirm the applicability of strength reduction factors proposed by ACI 440.2R-02 for general purpose. The strength reduction factors proposed in the present study are useful for durability based analysis and design of RC beams externally strengthened with CFRP plates and fabrics and exposed to a specific independent environmental condition (Appendix A). It should be noted, however, that the results of the present study are based on the study of two beams of each category. Therefore, with this limited data, generalization will not be accurate, and proper statistical analysis of data cannot be done.

To examine the effect of repeated loads on the ultimate failure loads of the beams strengthened with CFRP plates and fabrics, beams strengthened with CFRP plates and CFRP fabrics were subjected to constant amplitude repeated load cycles with a frequency of 3.25 Hz. Three constant amplitude load ranges equal to 15, 25, and 40% of the ultimate failure loads of the strengthened beams were considered. A set of four beams (Table 1) consisting of two beams strengthened with CFRP plates and two beams strengthened with CFRP fabrics were subjected to each load range for a total of 2 million cycles. It should be noted that the beams subjected to repeated load ranges were not exposed to any environmental conditions.

The load deflection responses (up to a load of 53.4 kN) were predicted by conducting static load tests at the beginning of repeated load cycles (0 cycle), and after 0.1, 1, and 2 million cycles. The ultimate load test on beams subjected to repeated loads was conducted only after execution of 2 million cycles of repeated load. The average ultimate load of unstrengthened beams, baseline beams, and the beams exposed to repeated loads and strengthened with CFRP plates and fabrics (P-R15, P-R25, P-R40, F-R15, F-R25, and F-R40) are presented in Table 6. These average ultimate loads are based on two test beams for each load range.

In Table 6, P refers to the beam strengthened with CFRP plate; F refers to the beam strengthened with CFRP fabrics; and R15, R25, and R40 refer to the repeated load range of magnitude 15, 25, and 40% of the ultimate strength of the baseline beams. It is shown in Table 6 that the baseline beam has 59% higher strength than the unstrengthened beam. It is observed from Table 6 that the constant amplitude repeated loads (applied for 2 million cycles) have no significant effect on the ultimate load of beams strengthened with CFRP plates and fabrics. The maximum variations in the ultimate loads of beams strengthened with CFRP plates and CFRP fabrics are 7.5 and 2.7%, respectively.

CONCLUSIONS

Based on the experimental results, the following conclusions can be made:

1. RC beams strengthened with CFRP plates are more susceptible to aggressive environmental conditions than the beams strengthened with CFRP fabrics. There is no significant effect, however, of repeated load cycles on the ultimate loads of beams strengthened with CFRP plates or CFRP fabrics for at least 2 million test cycles;

2. The load-carrying capacity of beams strengthened with CFRP plates is reduced after long-term exposure to 100% humidity, dry heat, freezing-and-thawing, and thermal expansion environmental conditionings. The beams strengthened with CFRP plates and exposed to saltwater and alkali-solutions, however, exhibit increased load-carrying capacity with respect to that of baseline beams, especially for short-term exposure; and

3. The onset of delamination was the primary mode of failure of beams strengthened with CFRP plates and fabrics with and without exposure to environmental conditions and repeated load cycles. The design approach presented herein appropriately demonstrates the evaluation of nominal and design moment strengths of strengthened beams along with failure modes.

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APPENDIX A

Design approach

The following section presents the durability-based design approach for an RC beam strengthened with CFRP plates and exposed to 100% humidity conditioning through a design example.

Problem—A deficient simply-supported RC beam is to be strengthened to carry a nominal ultimate midspan load of 72 kN (16.2 kips) using a 4-point loading system (refer to Fig. 8) in addition to its self-weight on a long-term basis under aggressive humidity conditions (hot water at 40 °C). Figure 1(b) shows the cross-sectional details of the beam. The total span of the beam is 2.743 m (9 ft), while the center-to-center distance between supports is 2.54 m (100 in.). The length of the central 4-point loading beam is 0.813 m (32 in.). The beam is internally reinforced with two Grade 60 steel bars of 9.5 and 15.9 mm (3/8 and 5/8 in.) diameter in compression and tension, respectively. Use of CFRP plate is recommended for external strengthening. Assume that the material being added through the placement in the enclosed space uses a wet lay-up process and adhesive bonding of prefabricated sections with ambient cure. Based on ACI 318-99[19] design procedure, nominal moment strength and corresponding strength reduction factor ϕ of the unstrengthened beam are 31.2 kN-m and 0.9, respectively. Design a suitable strengthening system using CFRP plates and structural epoxy. The material properties of CFRP plate and structural epoxy are given in Table 2 and 3, respectively.

Solution—The design steps for the CFRP-strengthened beam are explained as follows.

Step 1: Check for unstrengthened moment limit[18]

- Design strength of unstrengthened beam ϕM_n without FRP = 0.90 × 31.2 = 28.1 kN-m.
- Self-weight of the beam W_d = 0.152 × 0.254 × 24 = 0.93 kN/m.
- Unfactored service moment before strengthening

$$M_D = W_d l^2/8 = \frac{0.93 \times 2.54^2}{8} = 0.75 \text{ kN-m}$$

- Unfactored service live load moment

$$M_L = \frac{72 \times 0.864}{2 \times 1.7} = 18.3 \text{ kN-m}$$

- Required strength[18] of unstrengthened beam = 1.2 M_D + 0.85 M_L = 1.2 × 0.75 + 0.85 × 18.3
 = 16.5 kN-m < (ϕM_n) without FRP

Thus, external strengthening of RC beam using CFRP plate is reasonable.

Step 2: Compute design material properties

- Design ultimate tensile strength of CFRP plate $f_{fd} = C_E f_{fu}$ = 0.95 × 2070 = 1966.5 MPa.
- Design rupture strain of CFRP plate $\varepsilon_{fd} = C_E \varepsilon_{fu}$ = 0.95 × 0.015 = 0.014.

Step 3: Compute existing substrate strain ε_{bi} (Arduini and Nanni[20])

- Characteristic strength of concrete f'_c = 31 MPa.
- Modulus of elasticity of concrete $E_c = 4733\ \sqrt{31}$ =

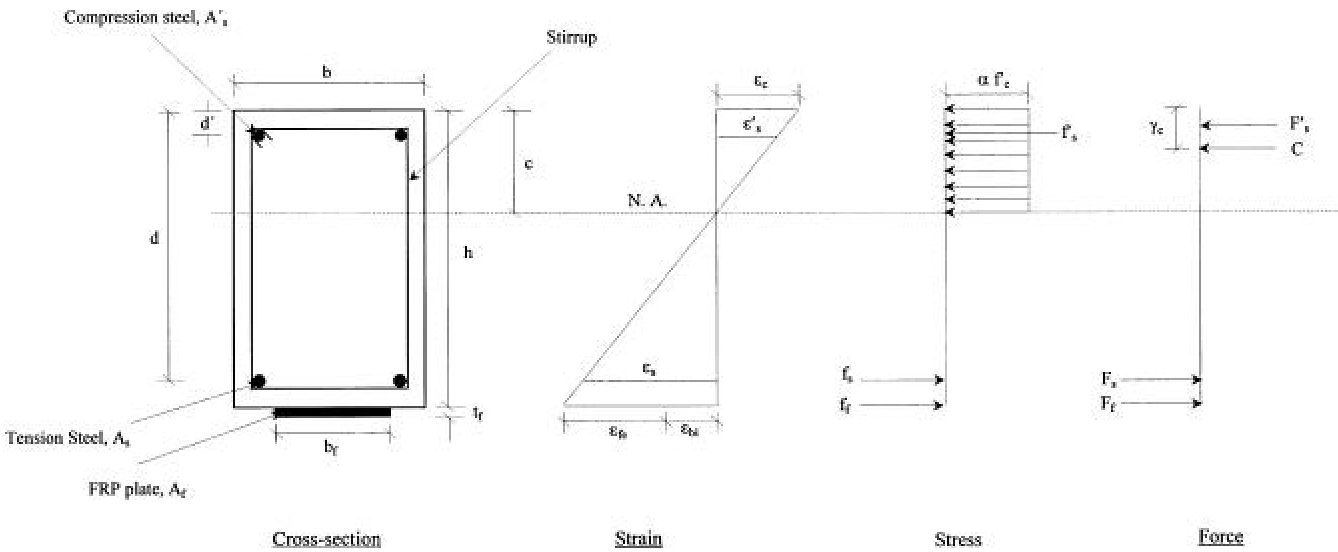

Fig. 12—Stress, strain, and force diagrams across depth of beam cross section.

26,352 MPa.
- Modular ratio m = 200,000/26,352 = 7.6.

Let the neutral axis depth of unstrengthened beam be c_o. Equating the first moment of tensile and compressive areas (based on concrete) about the neutral axis results in Eq. (1).

$$c_o^2 + 54.102\,c_o - 8987.1 = 0 \qquad (1)$$

- From the solution of Eq. (1), c_o = 71.5 mm.
- Transformed moment of inertia of elastic cracked unstrengthened beam section $I_{tro} = 78.252 \times 10^6$ mm^4.
- Total depth of beam h = 254 mm.
- Existing substrate strain.

$$\varepsilon_{bi} = \frac{M_o(h - c_o)}{E_c I_{tro}} = \frac{0.75\times10^6(254 - 71.5)}{26{,}352 \times 78.252\times10^6} = 66.40\times10^{-6}$$

Step 4: Compute balanced plate ratio $\rho_{f,b}$ (Saadatmanesh and Malek[21])

Balanced plate ratio gives the maximum cross-sectional area of the plate to assure yielding of the tensile reinforcement and crushing of the concrete simultaneously. The balanced plate ratio should be calculated depending on whether compression steel yields or not.
- Ultimate concrete strain ε_u = 0.003.
- Yield strain of steel =

$$\varepsilon_y = \frac{414}{200,000} = 2.1\times10^{-3}$$

- Effective depth of the beam d = 211 mm.
- Critical compression depth

$$d_c = \frac{\varepsilon_u - \varepsilon_y}{\varepsilon_u + \varepsilon_y} d = 37.3 \text{ mm}$$

- Distance of centroid of compressive steel from the extreme compression fiber d' = 39.7 mm.

Here, $d' > d_c \Rightarrow$ compression steel does not yield at the balanced condition.
- Value of delamination factor k_m (ACI Committee 440[18] and REPLARK SYSTEM[22]) can be obtained using Eq. (2), where γ equals 1.5 (International Federation for Structural Concrete[23]) and n equals 1.
- Mean tensile strength of concrete $f_{ctm} = 0.50\sqrt{31}$ = 2.78 MPa (ACI Committee 318[19]).

$$k_m = \frac{1.0(f'_c f_{ctm})^{1/4}}{1.2\,n t_f \gamma \varepsilon_{fd}(E_f)^{1/2}} \le 0.5 \qquad (2)$$

$$= \frac{1.0}{1.2\times1\times1.2\times1.5\times0.014}\,\frac{(31.0\times2.78)^{1/4}}{(138{,}000)^{1/2}} = 0.27 < 0.5$$

- $k_m\varepsilon_{fd} = 0.27 \times 0.014 = 3.78 \times 10^{-3}$
- Neutral axis depth ratio (c/d)

$$k_1 = \frac{\varepsilon_u}{\varepsilon_u + \varepsilon_y} = \frac{0.003}{0.003 + 2.1\times10^{-3}} = 0.588$$

- Cross-sectional area of compressive steel A'_s = 142 mm^2.
- Cross-sectional area of tensile steel A_s = 400 mm^2.
- Compressive reinforcement ratio

$$\rho' = \frac{A'_s}{b\times d} = \frac{142}{152\times211} = 4.43\times10^{-3}$$

- Tensile reinforcement ratio

$$\rho = \frac{A_s}{b \times d} = \frac{400}{152 \times 211} = 0.012$$

- Effective strain in the CFRP plates

$$\varepsilon_{fe} = \frac{(h - k_1 d)}{k_1 d}\varepsilon_u - \varepsilon_{bi}$$

$$= \frac{(254 - 0.588 \times 211)}{0.588 \times 211} \times 0.003 - 66.4 \times 10^{-6}$$

$$= 3.08 \times 10^{-3} \le k_m \varepsilon_{fd}$$

- Strain in the concrete corresponding to maximum stress

$$\varepsilon_o = \frac{2 f'_c}{E_c} = \frac{2 \times 31}{26{,}352} = 2.4 \times 10^{-3} < \varepsilon_u$$

- α = mean stress factor (An, Saadatmanesh, and Ehsani[24])

$$= \frac{\varepsilon_c}{\varepsilon_o} - \frac{\varepsilon_c^2}{3\varepsilon_o^2} \quad \text{for} \quad 0 \le \varepsilon_c \le \varepsilon_o \tag{3a}$$

$$= 1 + \frac{\varepsilon_c}{\varepsilon_o}\left(1 - \frac{\varepsilon_c}{3\varepsilon_o} - \frac{\varepsilon_o^2}{\varepsilon_c^2}\right) - \left(\frac{0.15}{0.004 - \varepsilon_o}\right)\left(\frac{\varepsilon_c}{2} - \varepsilon_o\right) - \tag{3b}$$

$$\left(\frac{0.075}{0.004 - \varepsilon_o}\right)\left(\frac{\varepsilon_o^2}{\varepsilon_c}\right) \text{for } \varepsilon_o \le \varepsilon_c \le \varepsilon_u$$

- From Eq. (3), for $\varepsilon_c = \varepsilon_u$, $\alpha = 0.92$.
- Thus, balanced plate ratio $\rho_{f,b}$ is given by Eq. (4).

$$\rho_{f,b} = \frac{\frac{(k_1 d - d')}{k_1 d}\varepsilon_u E_s \rho' + \alpha f'_c k_1 - \rho f_y}{\varepsilon_{fe} E_f} \tag{4}$$

$$= \frac{\frac{0.588 \times 211 - 39.7}{0.588 \times 211} \times 0.003 \times 0.200 \times 10^3 + 0.92 \times 31 \times 0.588 - 0.012 \times 414}{3.08 \times 10^{-3} \times 138{,}000}$$

$$= 0.03$$

Step 5: Compute maximum allowable plate ratio $\rho_{f,max}$

- $\rho_{f,max} = 0.75 \times 0.03 = 22.5 \times 10^{-3}$.

Step 6: Selection of CFRP plate size

Choose two plates of 76 × 1.2 mm dimensions and bonding them side by side along the width of beam cross-section.

- Total width of bonded plates $b_f = 152$ mm.
- Total thickness of plate $n\,t_f = 1 \times 1.2$ mm.
- Plate ratio

$$\rho_f = \frac{152 \times 1.2}{152 \times 211} = 5.69 \times 10^{-3} < \rho_{f,max}$$

Step 7: Compute balanced plate ratio $\rho_{f,bb}$ to determine failure modes

The balanced ratio $\rho_{f,bb}$ refers to the condition at which the maximum compressive stress in the concrete and the maximum effective tensile stress in the composite plate reach simultaneously. This can be used to characterize the two primary modes of failure such as crushing of concrete and plate failure by onset of delamination.

- Neutral axis depth coefficient

$$k_2 = \frac{\varepsilon_u}{\varepsilon_u + k_m \varepsilon_{fd} + \varepsilon_{bi}}$$

$$= \frac{0.003}{0.003 + 0.27 \times 0.014 + 66.4 \times 10^{-6}} = 0.438$$

- Strain in compressive steel

$$\varepsilon'_s = \left(1 - \frac{39.7}{0.438 \times 211}\right) \times 0.003 = 1.71 \times 10^{-3} < \varepsilon_y$$

$$\rho_{f,bb} = \frac{\alpha f'_c k_2 \frac{h}{d} + \varepsilon'_s E_s \rho' - \varepsilon_y E_s \rho}{k_m \varepsilon_{fd} E_f}$$

$$= \frac{0.92 \times 31 \times 0.438 \times \frac{254}{211} + (1.71 \times 10^{-3} \times 4.43 \times 10^{-3} - 2.1 \times 10^{-3} \times 0.012) \times 200 \times 10^3}{0.27 \times 0.014 \times 138{,}000}$$

$$= 2.2 \times 10^{-2} > \rho_f$$

Because the actual plate area is less than the balanced plate area (at ultimate condition), the plate failure by the onset of delamination will govern the design.

Step 8: Compute critical plate ratio $\rho_{f,fc}$

$$c = \frac{\varepsilon_y h + k_m \varepsilon_{fd} d'}{k_m \varepsilon_{fd} + \varepsilon_y}$$

$$= \frac{2.1 \times 10^{-3} \times 254 + 0.27 \times 0.014 \times 39.7}{0.27 \times 0.014 + 2.1 \times 10^{-3}} = 116.2 \text{ mm}$$

$$\rho_{f,cf} = \frac{\alpha f'_c \frac{c}{d} + (\rho' - \rho) f_y}{k_m \varepsilon_{fd} E_f}$$

$$= \frac{0.92 \times 31 \times \frac{116.2}{211} + (4.43 \times 10^{-3} - 0.012) \times 414}{0.27 \times 0.014 \times 138{,}000}$$

$$= 2.4 \times 10^{-3} > \rho_f$$

Because $\rho_{f,cf}$ is greater than ρ_f, the condition of yielding of compression steel at plate failure condition is not satisfied. Thus, nominal moment strength[9] of strengthened beam will be based on plate failure, yielding of tensile steel, and no yielding of compression steel.

Step 9: Compute nominal moment strength M_n of strengthened beam

Figure 12 shows the strain, stress, and force diagrams across the depth of cross section at the ultimate load condition.

$$k_m \varepsilon_{fd} = 3.78 \times 10^{-3}$$
$$\varepsilon_o = 2.4 \times 10^{-3}$$

- Strain in concrete

$$\varepsilon_c = \frac{(k_m \varepsilon_{fd} + \varepsilon_{bi})c}{h - c}$$

- Strain in compression steel

$$\varepsilon'_s = \frac{(c - 39.7)\varepsilon_c}{c}$$

- Assume c = 85 mm

$$\varepsilon_c = 1.93 \times 10^{-3} < \varepsilon_u$$
$$\varepsilon'_s = 1.0 \times 10^{-3} < \varepsilon_y$$

- From Eq. (3a), α = 0.58.
- From the equilibrium of forces,

$$\alpha f'_c\, bc + A'_s f'_s = A_f k_m \varepsilon_{fd} E_f + A_s f_s \qquad (5)$$

where

- Total cross-sectional area of CFRP plate A_f = 181.9 mm^2.
- Stress in tensile steel $f_s = f_y$ (yield stress of steel) = 414 MPa.
- Stress in compressive steel

$$f'_s = \frac{386(c - 39.7)}{c}$$

- Solving Eq. (5) after substituting the parametric values in terms of c, c = 83.4 mm ≅ assumed value of c; Thus, take c = 85 mm.

The ratio of the depth of centroid of resultant concrete compression force to the depth of the neutral axis can be computed using Eq. (6) (An, Saadatmanesh, and Ehsani[24]).

$$\beta_1 = \frac{\frac{1}{3} - \frac{\varepsilon_c}{12\varepsilon_o}}{1 - \frac{\varepsilon_c}{3\varepsilon_o}} \quad \text{if} \quad 0 \le \varepsilon_c \le \varepsilon_o \qquad (6a)$$

$$= 1 - \frac{\varepsilon_c^3 - 5.1\varepsilon_o\varepsilon_c^2 - 0.004\,\varepsilon_c^2 + 0.024\varepsilon_c^2}{\varepsilon_c(3.925\varepsilon_c^2 - 10.2\,\varepsilon_c\varepsilon_c - 0.9\varepsilon_c^2 - 0.16\varepsilon_c + 0.048\varepsilon_c)} \qquad (6b)$$

$$\text{if } \varepsilon_o \le \varepsilon_c \le \varepsilon_u$$

- From Eq. (6a), β_1 = 0.36.
- Depth of centroid of resultant concrete compression force from the extreme compression fiber, $\gamma_c = \beta_1 c$ = 0.36 × 85 = 30.6 mm.
- Here, strength reduction factor, ψ (Table 5) for hot water conditioning (100% humidity) = 0.70.
- Nominal moment strength of strengthened beam, M_n is given by Eq. (7).

$$M_n = A'_s f'_s (d' - \gamma_c) + A_s f_s (d - \gamma_c) + \psi A_f E_f k_m \varepsilon_{fd}(h - \gamma_c) \qquad (7)$$

= 28.4(39.7 – 30.6) + 165.6(211 – 30.6) + 0.70× 94.938(254 – 30.6) = 44,979 kN-mm = 45 kN-m

- Factored dead load moment = 1.4 M_D = 1.05 kN-m.
- Nominal ultimate load of beam = ([45 – 1.05] × 2)/0.864 = 101.7 kN > 72 kN.
- Required moment strength of the beam M_u can be determined using Eq. (8).

$$M_u = 1.4\, M_D + 1.7\, M_L \qquad (8)$$

$$= 1.4 \times 0.75 + \frac{72 \times 0.864}{2} = 32.2 \text{ kN-m}$$

Step 10: Compute design moment strength of strengthened beam

- Strain in tensile steel at ultimate load of strengthened beam,

$$\varepsilon_s = \frac{1.93 \times 10^{-3}(211 - 85)}{85} = 0.0029$$

- Strength reduction factor[18]

$$\phi = 0.70 + 0.20\, \frac{(\varepsilon_s - \varepsilon_y)}{(0.005 - \varepsilon_y)} = 0.76$$

$$M_d = \phi M_n = 0.76 \times M_n = 34.2 \text{ kN.m} > M_u$$

Step 11: Check for stresses under sustained service load condition

In the present problem, sustained service load is only self-weight of the beam causing flexural stresses, hence only service dead load is considered for checking the safety of CFRP plate against failure due to creep rupture.

- Thus, moment due to sustained service load $M_s = M_D$ = 0.75 kN-m = 750 × 10^3 N-mm.
- Modular ratio m_f = 138,000/26,352 = 5.24 and modular ratio m = 7.6.

Let the neutral axis depth of the strengthened beam corresponding to the service load condition is c. Equating the first moment of the compression and tension area (based on concrete) about the neutral axis results in the following quadratic equation

$$c^2 + 64.88c - 12{,}116.9 = 0 \tag{9}$$

- From the solution of Eq. (9), c = 82 mm = kd; where k is the neutral axis depth coefficient.
- Maximum stress in tensile steel under sustained service loads $f_{s,s}$

$$= \frac{\left[M_s + \varepsilon_{bi} A_f E_f\left(h - \frac{kd}{3}\right)\right](d - kd)E_s}{A_s E_s\left(d - \frac{kd}{3}\right)(d - kd) + A'_s E_s\left(\frac{kd}{3} - d'\right)(kd - d') + A_f E_f\left(h - \frac{kd}{3}\right)(h - kd)}$$

$$= \text{A} = \left[750\times10^3 + 66.4\times10^{-6}\times182\times138{,}000\left(254 - \frac{82}{3}\right)\right]$$

$$\text{B} = (211 - 82)\times200{,}000$$

$$\text{C} = 400\times200{,}000\left(211 - \frac{82}{3}\right)(211 - 82)$$

$$\text{D} = 142\times200{,}000\left(\frac{82}{3} - 39.7\right)(82 - 39.7)$$

$$\text{E} = 182\times138{,}000\left(254 - \frac{82}{3}\right)(254 - 82)$$

$$= \frac{(\text{A})(\text{B})}{[\text{C}] + [\text{D}] + [\text{E}]} = 10.2\ \text{MPa} < 0.8 f_y$$

- Maximum compressive stress in concrete under sustained service load $f_{c,s}$

$$= f_{s,s}\left(\frac{E_c}{E_s}\right)\frac{kd}{(d - kd)}$$

$$= 10.2\times\left(\frac{1}{7.6}\right)\times\frac{82}{(211 - 82)} = 0.85\ \text{MPa} < 0.45 f'_c$$

- Maximum stress in CFRP plate under sustained load $f_{fe,s}$

$$= f_{s,s}\left(\frac{E_f}{E_s}\right)\left(\frac{h - kd}{d - kd}\right) - \varepsilon_{bi}E_f$$

$$= 10.2\times\left(\frac{138{,}000}{200{,}000}\right)\left(\frac{254 - 82}{211 - 82}\right) - 66.4\times10^{-6}\times138{,}000$$

$$= 0.22\ \text{MPa} < 0.55 f_{fd}$$

- Maximum stress in compression steel under sustained load $f'_{s,s}$

$$= f_{s,s}\left(\frac{kd - d'}{h - kd}\right)$$

$$= 10.2\times\frac{82 - 39.7}{211 - 82} = 3.34\ \text{MPa} < 0.4 f_y$$

- k = neutral axis depth coefficient at service load condition.

Since the service load stresses under the sustained self-weight of the beam are under allowable limits, the CFRP plates will have adequate safety against failure due to creep rupture.

NOTATION

A_f	=	cross-sectional area of FRP plate, mm^2
A_s	=	cross-sectional area of tension steel reinforcement, mm^2
A'_s	=	cross-sectional area of compression reinforcement, mm^2
b	=	width of beam, mm
b_f	=	total width of plates, mm
C	=	resultant compressive force in concrete, kN
C_E	=	environmental tensile strength reduction factor for FRP materials
c	=	depth of neutral axis of strengthened beam from extreme compression fiber, mm
c_o	=	depth of neutral axis of unstrengthened beam from extreme compression fiber, mm
d, d'	=	depth of centroid of tensile and compression steel reinforcements from extreme compression fiber, respectively, mm
d_c	=	critical compression depth, mm
E_c	=	modulus of elasticity of concrete, MPa
E_f	=	modulus of elasticity of FRP material, MPa
E_s	=	modulus of elasticity of steel, MPa
F_f	=	resultant force in FRP plate at ultimate condition, kN
F_s	=	resultant force in tensile steel at ultimate condition, kN
F'_s	=	resultant force in compressive steel at ultimate condition, kN
f'_c	=	characteristic strength of concrete, MPa
$f_{c,s}$	=	maximum compressive stress in concrete under sustained service loads, MPa
f_f	=	stress in FRP plate at ultimate condition, MPa
f_{fe}	=	effective stress in CFRP plate, MPa
$f_{fe,s}$	=	maximum stress in CFRP plate under sustained load, MPa
f_{fu}	=	specified tensile strength of FRP plate, MPa
f_s	=	stress in tensile steel at ultimate condition, MPa
f'_s	=	stress in compressive steel at ultimate condition, MPa
$f_{s,s}$	=	maximum stress in tensile steel under sustained service loads, MPa
$f'_{s,s}$	=	maximum stress in compression steel under sustained service loads, MPa
f_y	=	yield stress of steel, MPa
h	=	overall depth of the beam, mm
I_{tro}	=	moment of inertia of the transformed cracked section of unstrengthened beam, mm^4
k	=	neutral axis depth factor at service load condition
k_m	=	bond-dependent coefficient for flexure
k_1, k_2	=	neutral axis depth factors at balanced and ultimate conditions, respectively
k_3	=	neutral axis depth factor corresponding to yielding of compression steel at crushing of concrete
M_D	=	unfactored maximum bending moment due to dead load, kN-m
M_d	=	design moment strength of strengthened beam, kN-m
M_L	=	unfactored maximum bending moment due to live load, kN-m
M_n	=	nominal moment strength of strengthened beam, kN-m
M_o	=	unfactored service moment acting on RC beam before upgrading, kN-m
M_s	=	unfactored moment due to sustained portion of service loads, kN-m
M_u	=	ultimate moment strength of strengthened beam, kN-m
m	=	modular ratio of steel and concrete
m_f	=	modular ratio of FRP plate and concrete
n	=	number of layers of CFRP plates
t_f	=	thickness of CFRP plate, mm
W_d	=	self-weight of beam, kN/m
α	=	mean stress factor
β_1	=	ratio of depth of centroid of resultant concrete compression force to depth of neutral axis
ε_{bi}	=	strain level in concrete substrate at time of CFRP installation
ε_c	=	concrete strain at extreme compression fiber at particular load
ε_{fd}	=	design strain for CFRP plate

ε_{fe} = effective design strain for CFRP plate
ε_{fu} = specified rupture strain for CFRP plate
ε_o = concrete strain corresponding to maximum concrete stress
ε_s = strain in tensile steel
ε'_s = strain in compressive steel
ε_u = ultimate concrete strain
ε_y = yield strain of steel
ϕ = strength reduction factor
ϕM_n = (without FRP) design moment strength of unstrengthened RC beam
γ_c = depth of centroid of resultant concrete compression force from extreme compression fiber, mm
ρ = tensile steel reinforcement ratio
ρ' = compressive steel reinforcement ratio
ρ_f = ratio of plate to beam cross-sectional area
$\rho_{f,b}$ = balanced plate ratio