

Concrete Repair with CFRP

Evaluating the durability of externally bonded carbon fiber-reinforced polymer plates and fabric exposed to the environment

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Carbon fiber-reinforced polymers (CFRP) are currently used worldwide to retrofit and repair structurally deficient infrastructures such as bridges and buildings. Using CFRP reinforcing bars in new concrete can eliminate potential corrosion problems and substantially increase a member's structural strength. When reinforced concrete (RC) members are strengthened with externally bonded CFRP, the bond between the CFRP and RC substrate significantly affects the member's load-carrying capacity. This article presents the effects of adverse environmental conditions on the deflections and ultimate load-carrying capacities of beams strengthened with externally bonded CFRP. Long-term exposure to humidity was most detrimental to the bond between the CFRP and the RC. Delamination was the primary failure mode for the tested beams. Furthermore, the author proposes strength-reduction factors Ψ associated with various independent environmental conditions.

PRIOR INVESTIGATIONS

Based on experimental evaluations of externally strengthened RC beams, David and Neuner¹ and Karbhari and Engineer² concluded that long-term exposure to humidity may cause a significant decrease in their load-carrying capacity. The study of Karbhari and Engineer² also revealed that, depending on the compatibility of the fibers and the resin, even short-term exposure of CFRP to humidity may significantly degrade the beam strengthening system. Similarly, Juska et al.³ analyzed data related to thermal

exposure and freezing and thawing and concluded that elevated temperature and freezing-and-thawing cycles have significant detrimental effects on FRP composite systems. Benmokrane et al.⁴ studied the effects of an alkaline solution on FRP composites and confirmed that an alkaline environment may cause degradation of both the stiffness and strength of various FRP composites.

78 BEAMS TESTED

Of the 78 RC beams tested, two were unstrengthened beams; four were reference beams not exposed to environmental conditions (two strengthened with CFRP plates and two strengthened with CFRP fabrics); and the remaining 72 beams were strengthened with CFRP and exposed to environmental conditions or repeated loads. One-half of the beams exposed to environmental conditions or repeated loads (36) were strengthened with CFRP plates and the other half with CFRP fabric. Sets of four strengthened beams (two beams reinforced with CFRP plates and two with CFRP fabric) were exposed for 1000, 3000, and 10,000 h to each environmental condition: 100% humidity, dry heat, alkaline solution, and saltwater solution. In addition, sets of four beams were also exposed to 350 and 700 freezing-and-thawing cycles and 35 thermal expansion cycles. A total of 12 strengthened beams were subjected to repeated load test cycles: four beams were used for each of the three repeated load ranges of magnitudes 15, 25, and 40% of the ultimate

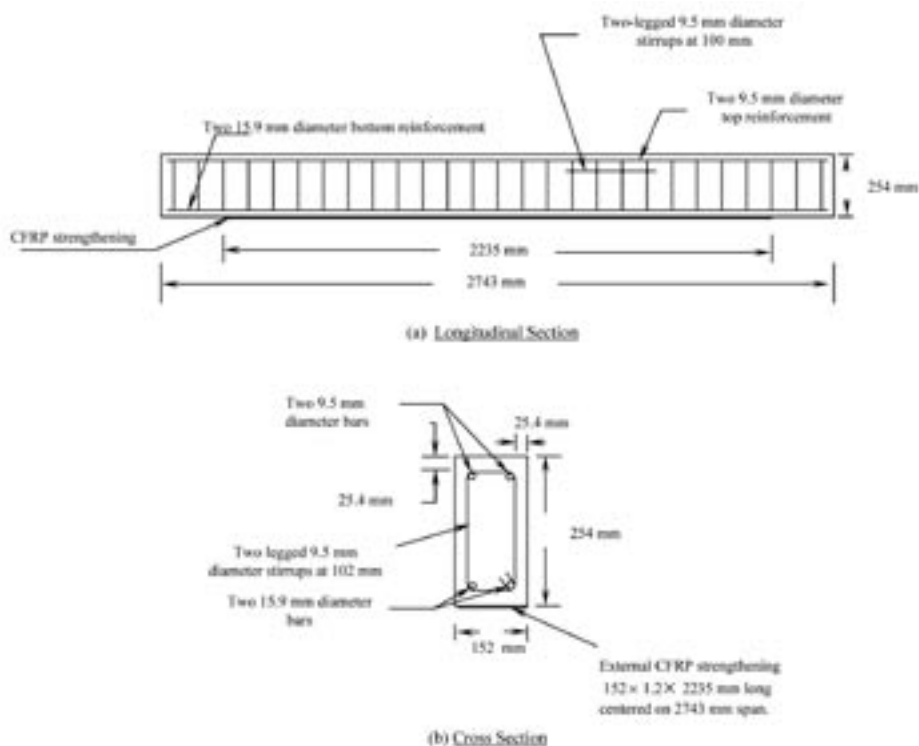


Fig. 1: Longitudinal and cross-sectional details of all RC beams in the experimental program
Note: 1 in. = 25.4 mm

TABLE 1:
PROPERTIES OF CFRP STRENGTHENING MATERIALS USED IN THIS STUDY

Property	CFRP plate	CFRP fabric
Width, mm	76.2	152
Thickness, mm	1.2	0.2
Average modulus of elasticity, GPa	138	227
Average ultimate strain, %	1.5	1.8
Average ultimate tensile strength, MPa	2070	2758

Note: 1 in. = 25.4 mm, 1 GPa = 1000 MPa = 145 ksi

TABLE 2:
TYPICAL PROPERTIES FOR EPOXIES USED TO BOND CFRP TO RC

Property	Structural epoxy	Saturating epoxy
Tensile strength, MPa	60.7	62 to 75.8
Adhesion strength, MPa	>2	>2
Flexural strength, MPa	100	103.4 to 131
Flexural modulus, GPa	2.14	2.41
Glass transition temperature T_g , °F	140	140

Note: 1 GPa = 1000 MPa = 145 ksi, °C = (°F - 32) × 5/9

strength of the strengthened beams. Brief details of the test beams and procedures⁵ are presented in the following sections.

DETAILS OF SPECIMEN CONSTRUCTION

Figure 1 shows the dimensions and the steel reinforcement of all beams in the experimental program. The specified concrete strength of the RC beams was 31 MPa (4500 psi) at 28 days, with a specified steel reinforcement yield strength of 414 MPa (60 ksi). Beams were either strengthened with one layer of CFRP plates or two layers of CFRP fabric. Each of these strengthening patterns results in the same ultimate strength for both types of beams. The following section explains the details of the repairs using CFRP.

REPAIRING WITH CFRP

The manufacturer's instructions were followed to bond the CFRP plates and fabrics to the test beams. A hand grinder and a masonry-grinding wheel were used to remove all irregularities on the concrete surface of the beam. The surfaces were sand-blasted to ensure proper bonding with the CFRP. Structural epoxy was used to fill voids and low spots on the surfaces of the beams and was allowed to cure for 24 h prior to CFRP application.

Fabric layers were 0.2-mm-thick (0.007 in.), 152-mm-wide (6 in.), and 2235-mm-long (88 in.). The first layer of CFRP fabric was bonded to the prepared surface of the concrete. Subsequently, the second layer of CFRP fabric was bonded over the first layer using the same epoxy. Hand rollers were used to properly bond the fabrics together and to remove any trapped air between them. It should be noted that the CFRP plates were bonded with structural epoxy while CFRP fabric used saturating epoxy. Table 1 presents the material properties of CFRP fabrics and plates, provided by the manufacturer, while Table 2 lists the properties of the structural epoxy and the saturating epoxy.

ENVIRONMENTAL CONDITIONING

Three stainless steel tanks contained either 100% humidity, alkaline solution, or saltwater solution. Each 3.05-m-long (10 ft), 1.22-m-wide (4 ft), and 1.22-m-deep (4 ft) tank could accommodate 12 beams (three layers of four beams each). Each layer consisted of two beams

strengthened with CFRP plates and two beams strengthened with CFRP fabric. Each tank had a heating blanket placed under the bottom surface to maintain the temperature of solution per ASTM;⁶⁻⁸ two pumps positioned at opposite corners of the tank bottom to ensure adequate water circulation; and thermocouples to continuously monitor the temperature inside. The top, middle, and bottom layers of beams were removed after 1000, 3000, and 10,000 h of a particular environmental condition, respectively. After each exposure, the beams were transported to the Structural Testing Center at Lawrence Technological University and instrumented for an ultimate load test. The 100% humidity condition at $38\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$ ($100\text{ }^{\circ}\text{F} \pm 3\text{ }^{\circ}\text{F}$) was maintained in the tank per ASTM D 2247-02, "Standard Practice for Testing Water Resistance of Coatings in 100% Relative Humidity,"⁶ while the alkaline and saltwater solutions at $23\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$ ($73\text{ }^{\circ}\text{F} \pm 3\text{ }^{\circ}\text{F}$) were prepared per ASTM C 581, "Standard Practice for Determining Chemical Resistance of Thermosetting Resins Used in Glass-Fiber-Reinforced Structures Intended for Liquid Service,"⁷ and ASTM D 1141, "Standard Practice for the Preparation of Substitute Ocean Water,"⁸ respectively. It should be noted that the pH of the alkaline solution was 9.5, and the saltwater solution had a concentration of 1500 ppm with a specific gravity of 1.022.

To examine the effect of dry heat on the beams strengthened with CFRP, a specially designed and manufactured dry-heat chamber was used to meet ASTM D 3045, "Standard Practice for Heat Aging of Plastics Without Load."⁹ The chamber was heated to $60\text{ }^{\circ}\text{C}$ ($140\text{ }^{\circ}\text{F}$) and the top, middle, and bottom layers of beams were kept under the steady heat for 1000, 3000, and 10,000 h, respectively. To determine the performance of beams in a freezing-and-thawing environment, beams were exposed to 350 and 700 freezing-and-thawing cycles in an environmental chamber designed and manufactured to meet ASTM C 666, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing,"¹⁰ Procedure B. A freezing-and-thawing cycle consisted of first lowering the temperature of the beams from $4\text{ }^{\circ}\text{C}$ to $-17.8\text{ }^{\circ}\text{C}$ ($40\text{ }^{\circ}\text{F}$ to $0\text{ }^{\circ}\text{F}$) and then returning them to $4\text{ }^{\circ}\text{C}$ ($40\text{ }^{\circ}\text{F}$). Air was used to freeze the beams and water to thaw them. The total duration of each freezing-and-thawing cycle was 4 h. The chamber used to perform the freezing and thawing, which was 6.1-m-long (20 ft), 3.6-m-wide (12 ft), and 2.7-m-deep (9 ft), was also used to examine the effect of 35 thermal expansion test cycles. During thermal expansion testing, the chamber was programmed for a maximum temperature of $75.5\text{ }^{\circ}\text{C}$ ($168\text{ }^{\circ}\text{F}$) and a maximum humidity of 100%. Each thermal expansion test cycle consisted of raising the temperature of a beam to $48.9\text{ }^{\circ}\text{C} \pm 1.5\text{ }^{\circ}\text{C}$ ($120\text{ }^{\circ}\text{F} \pm 2\text{ }^{\circ}\text{F}$) and then cooling

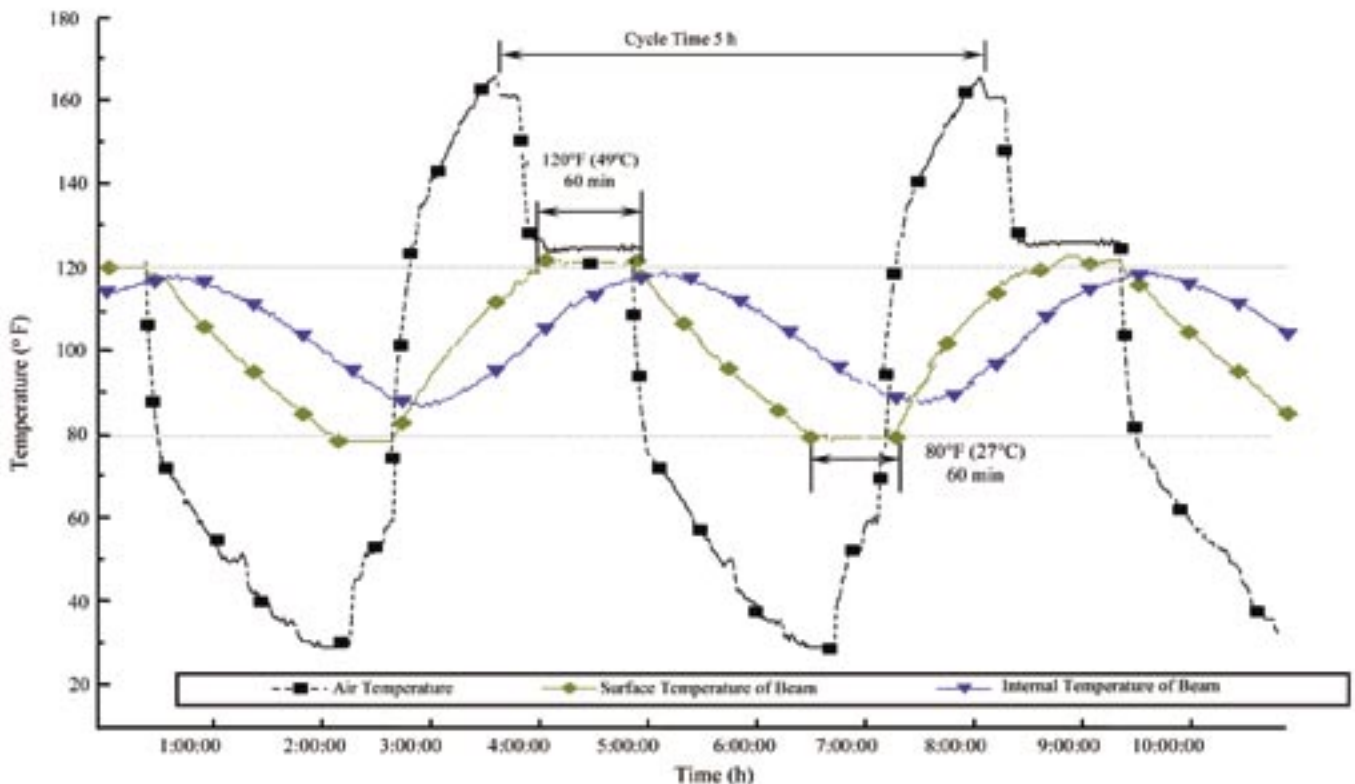


Fig. 2: Thermal expansion test cycles, which consisted of raising the temperature of a beam to $48.9\text{ }^{\circ}\text{C} \pm 1.5\text{ }^{\circ}\text{C}$ ($120\text{ }^{\circ}\text{F} \pm 2\text{ }^{\circ}\text{F}$) and then cooling it down to $26.7\text{ }^{\circ}\text{C} \pm 1.5\text{ }^{\circ}\text{C}$ ($80\text{ }^{\circ}\text{F} \pm 2\text{ }^{\circ}\text{F}$) in 5 h. Note: $^{\circ}\text{C} = (^{\circ}\text{F} - 32) \times 5/9$

it down to $26.7\text{ }^{\circ}\text{C} \pm 1.5\text{ }^{\circ}\text{C}$ ($80\text{ }^{\circ}\text{F} \pm 2\text{ }^{\circ}\text{F}$) (ASTM C 531, “Standard Test Method for Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistant Mortars, Grouts, Monolithic Surfacing, and Polymer Concretes”¹¹), in a total duration of 5 h (Fig. 2). As in the case of beams exposed to 100% humidity, and alkaline and saltwater solutions, beams exposed to dry heat, freezing and thawing, and thermal expansion were removed from the chambers and transported to the Structural Testing Center for ultimate load testing.

ULTIMATE LOAD TEST

An ultimate load test was conducted on each test beam using a four-point loading test. The center-to-center distance between supports was 2.54 m (100 in.), with a constant moment region of 0.81 m (32 in.) centered on the span. Before ultimate failure, beams were loaded and unloaded in two stages. During the first stage, beams were loaded up to a total applied load of 53.4 kN (12 kip)

and unloaded to zero load. In the second stage, beams were reloaded to 106.8 kN (24 kip) and then unloaded to zero load. Finally, all beams were loaded to failure.

ENVIRONMENTAL EFFECTS

Figure 3 compares the load-deflection responses of reference beams reinforced with CFRP plates (beams without environmental exposure) and beams strengthened with CFRP plates and exposed to 10,000 h of 100% humidity. These results show the strength of the reference RC beam increased by 59%. Exposure to humidity for 10,000 h, however, reduced the ultimate load of strengthened beams by about 33%. This 33% reduction in the ultimate load equates to about 87% loss of the gain of the strength attributed to the CFRP. It should be noted that before failure, the stiffnesses of the reference beams and those exposed to 100% humidity were essentially the same. As shown in Fig. 3, both the reference beams and the beams strengthened with CFRP plates and exposed to 10,000 h of

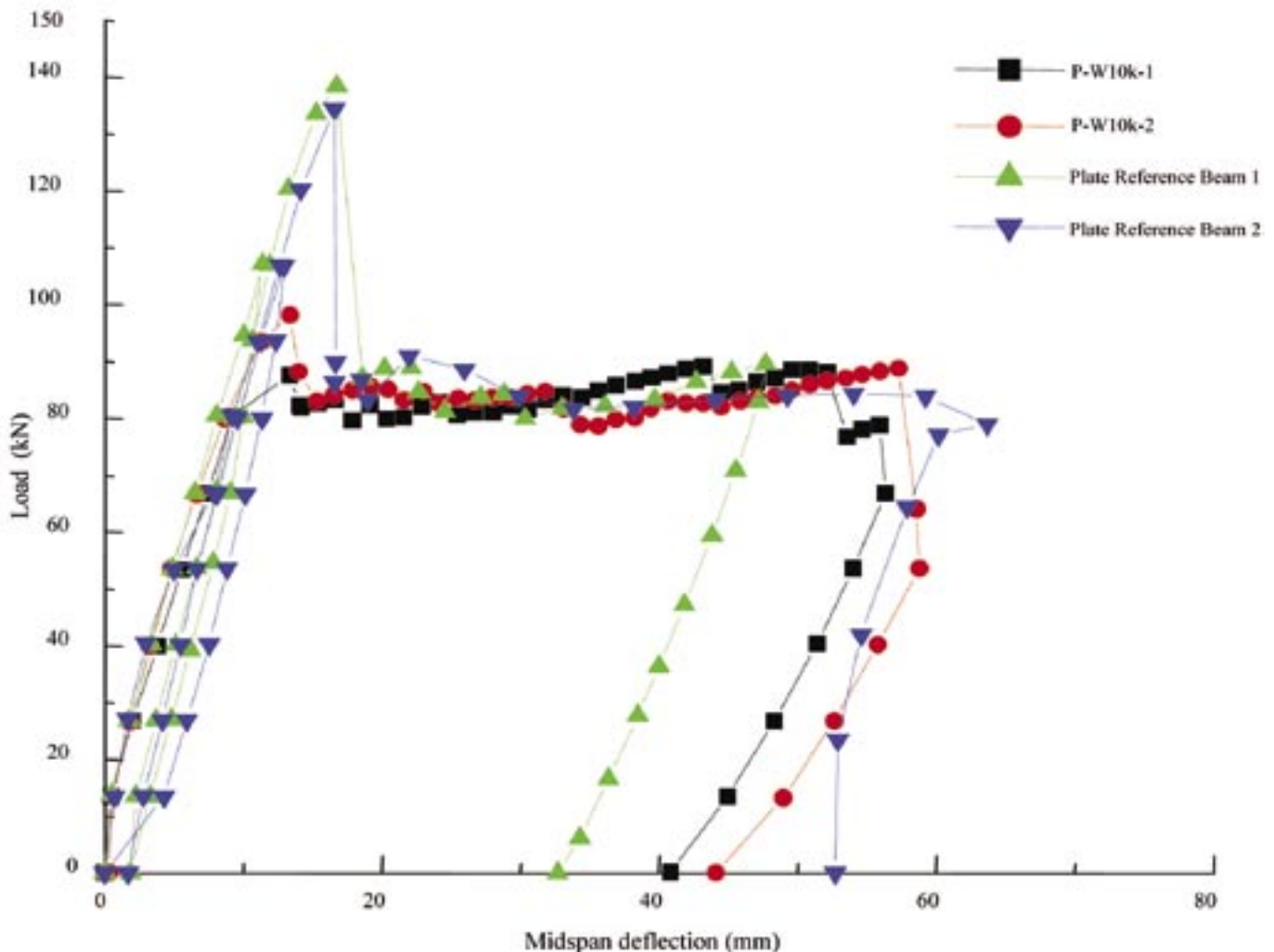


Fig. 3: Load-versus-deflection relationships for beams strengthened with CFRP plates exposed to 10,000 h of 100% humidity at 100 °F (38 °C). Note: 1 in. = 25.4 mm, 1 kN = 225 lb

humidity (P-W10k-1, 2) show a sudden drop of the load followed by a large deflection at a constant load before their failure. This behavior 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 load. Note that a similar load-deflection response was observed for each of the other test beams, except that other environmental exposures did not cause as great of a load reduction effect. Figure 4 shows the failure of the beam strengthened with CFRP plates after 10,000 h of exposure to 100% humidity. Similar failure modes were observed for the beams strengthened with CFRP fabrics.

Figure 5 shows the average ultimate failure loads of the beams strengthened with CFRP plates and exposed to dry heat, humidity, salt water, and alkaline solution for 1000, 3000, and 10,000 h. As mentioned previously, the external strengthening of RC beams using CFRP plates increased their load-carrying capacity by about 59%. It is observed that unlike the case of 100% humidity, the reduction in the strength of beams due to dry heat is not significant. The saltwater and alkaline solutions do not reduce the load-carrying capacity of beams, especially for short-term exposure (about 3000 h). Figure 6 presents the corresponding average ultimate loads of the beams strengthened with CFRP plates and exposed to freezing-and-thawing and thermal expansion test cycles. Thirty-five thermal expansion test cycles reduced the strength of beams by about 15%,

whereas 350 and 700 freezing-and-thawing cycles decreased the load-carrying capacity of the beams by about 3.3 and 9.5%, respectively. Similarly, Fig. 7 and 8 show the comparison of ultimate loads of beams strengthened with CFRP fabrics and exposed to various independent environmental conditions. It should be noted that the concrete specimens were old enough to avoid the contribution of young concrete to the strength reduction.

Short-term exposure (up to 3000 h) to dry-heat conditioning slightly increased the load-carrying capacity of the beams strengthened with CFRP fabrics compared with that of the reference beams (Fig. 7). Humidity and saltwater solution also decreased the load-carrying capacity of the beams strengthened with CFRP fabrics; however, duration of exposure to humidity and saltwater solution had no significant effect, as observed in the case of beams strengthened with CFRP plates (Fig. 5). It is worth noting



Fig. 4: Ultimate load failure of a beam strengthened with CFRP plates and subjected to 10,000 h of 100% humidity

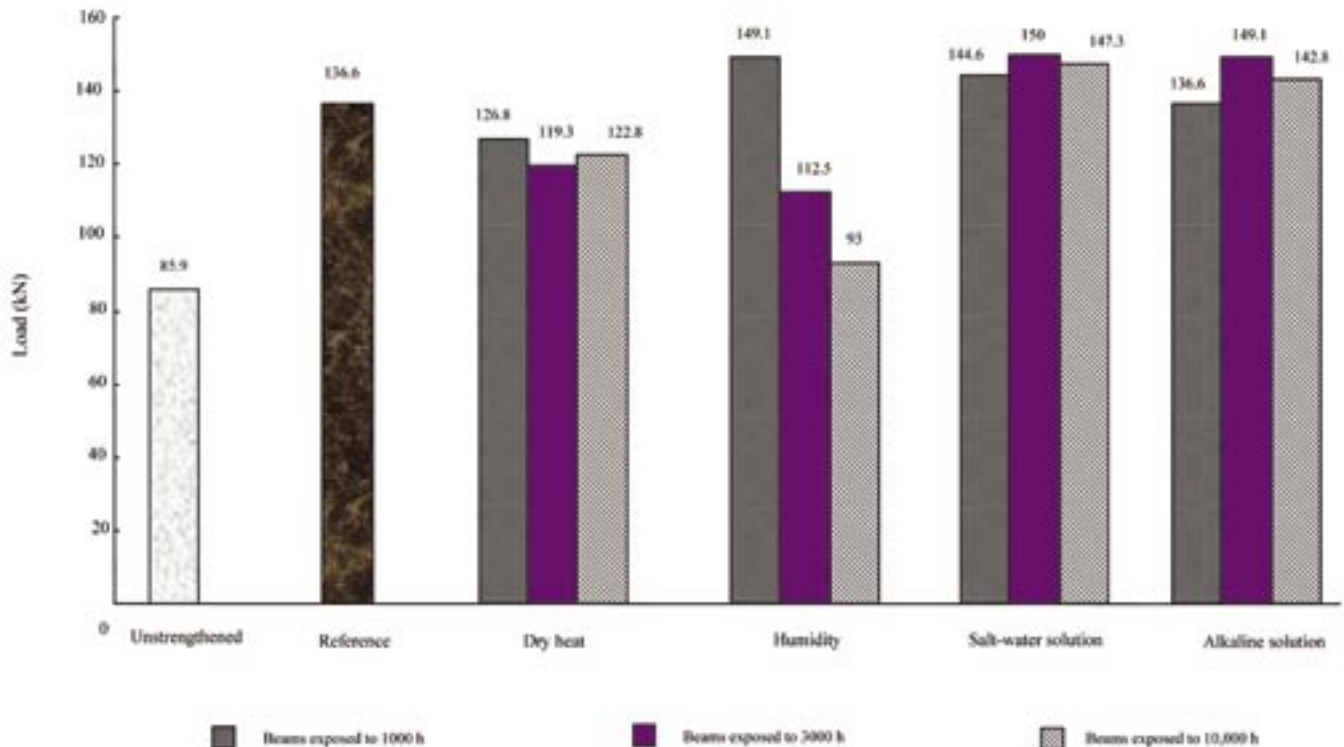


Fig. 5: Average ultimate failure loads for beams strengthened with CFRP plates. Note: 1 kN = 225 lb

that the reduction in the ultimate load-carrying capacity of beams strengthened with CFRP fabrics and exposed to saltwater solution is the same (about 5.3%), irrespective of the duration of exposure. Similarly, thermal expansion test cycles had no significant effect on the load-carrying capacity of the beams, while 700 freezing-and-thawing test cycles reduced the load-carrying capacity of the beam by about 13% (Fig. 8).

Based on the experimental results of beams strengthened with CFRP and exposed to various independent environmental conditions, Table 3 presents the proposed strength reduction factors associated with 100% humidity, dry heat, alkaline solution, freezing and thawing, and saltwater solution.⁵ These strength reduction factors are useful for durability-based analysis and design⁵ of

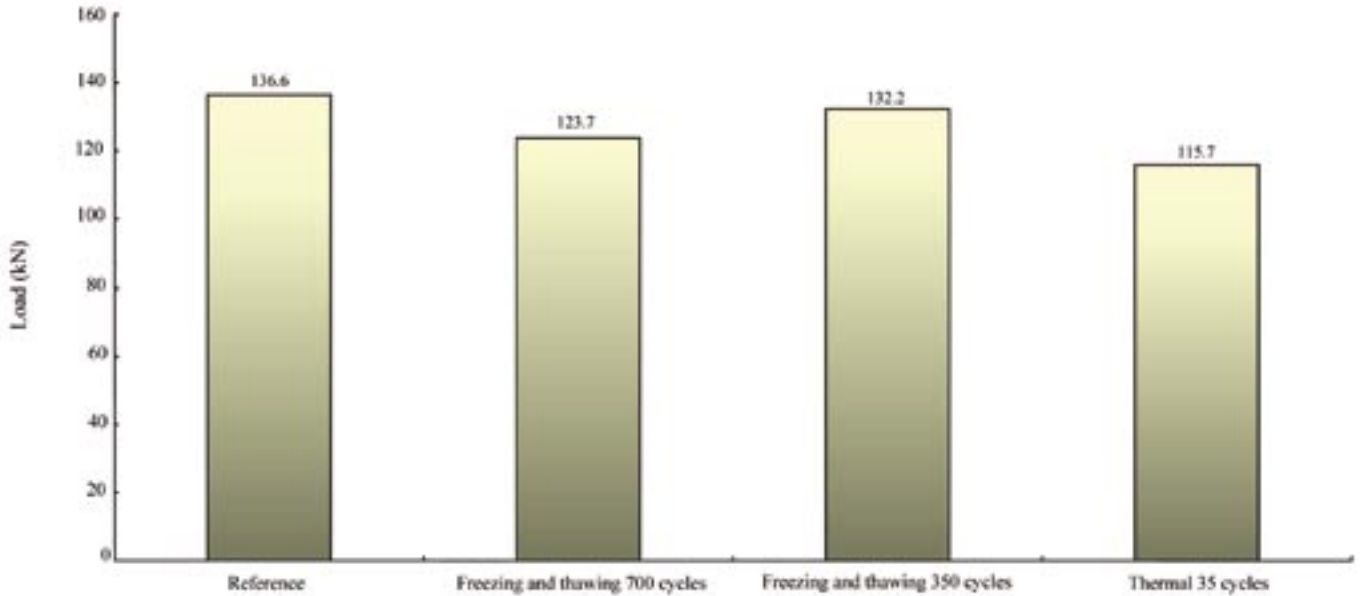


Fig. 6: Average ultimate failure loads for beams strengthened with CFRP plates after exposure to freezing-and-thawing and thermal expansion test cycles. Note: 1 kN = 225 lb

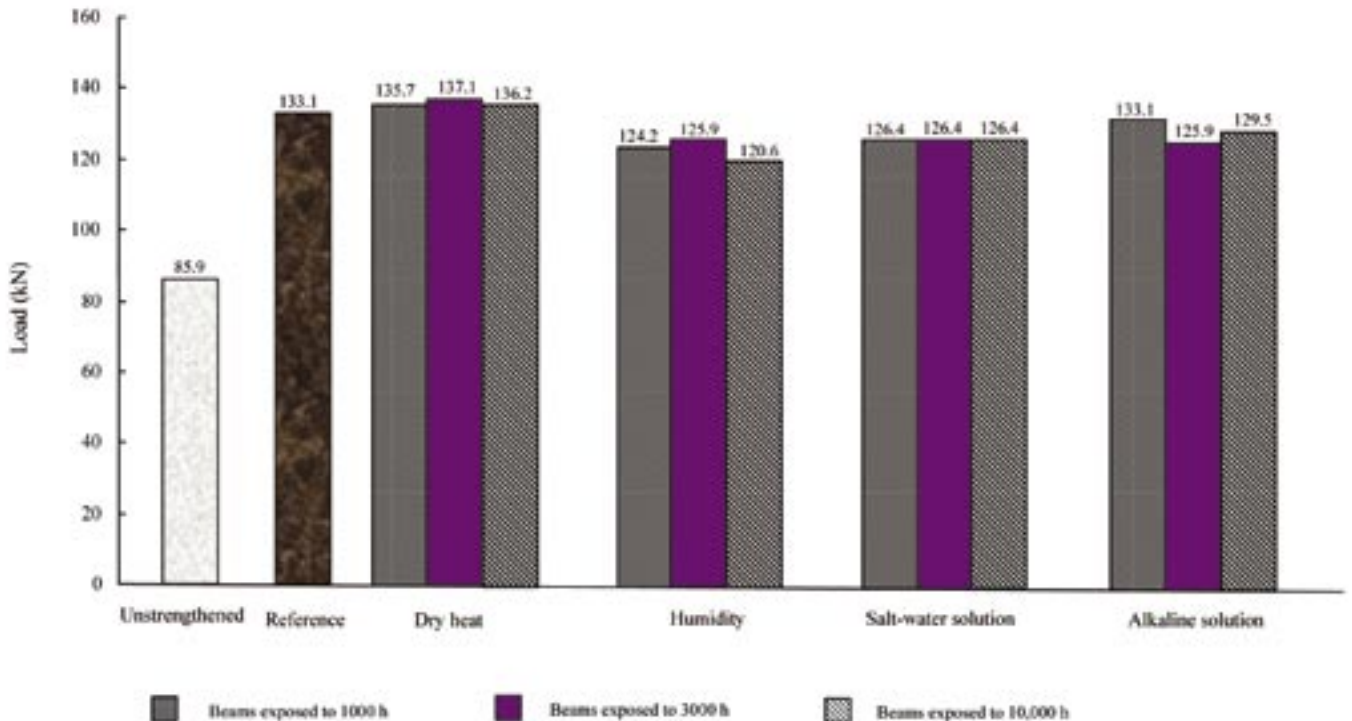


Fig. 7: Average ultimate failure loads for beams strengthened with CFRP fabrics. Note: 1 kN = 225 lb

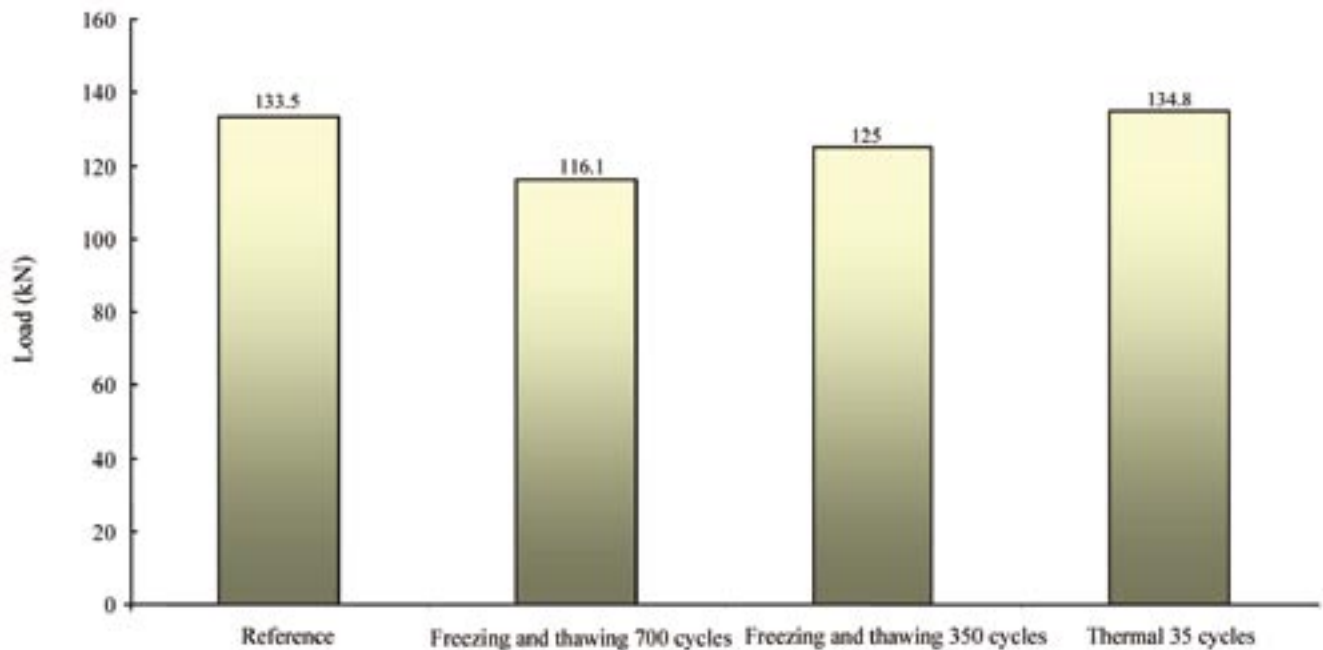


Fig. 8: Average ultimate failure loads for beams strengthened with CFRP fabrics exposed to thermal cycles. Note: 1 kN = 225 lb

TABLE 3:
CFRP STRENGTH REDUCTION FACTORS Ψ FOR DIFFERENT ENVIRONMENTAL CONDITIONS

Environmental condition	CFRP plate	CFRP fabric
100% humidity	0.70	0.90
Dry heat	0.90	1.00
Alkalinity	1.00	0.90
Freezing and thawing	0.90	0.85
Salinity	0.95	0.90

TABLE 4:
ULTIMATE FAILURE LOADS OF BEAMS SUBJECT TO REPEATED LOADS

Beam	Ultimate failure load, kN
Unstrengthened	85.9
Plate reference	138.4
P-R15	126.4
P-R25	129.9
P-R40	146.9
Fabric reference	129.5
F-R15	125.9
F-R25	125.9
F-R40	130.4

Note: 1 kN = 225 lb

RC beams externally strengthened with CFRP plates or fabric and exposed to specific environmental conditions. Each strength reduction factor is based on the ratio of the ultimate load of strengthened beams exposed to independent environmental condition to that of the unexposed beam.

To examine the effect of repeated loads on the load-carrying capacity of beams strengthened with CFRP, these beams were subjected to constant amplitude repeated loads at a frequency of 3.25 Hz for 2 million cycles. Three constant amplitude load ranges equal to 15, 25, and 40% of the ultimate failure loads of the strengthened beams were considered. Table 4 presents the average ultimate loads of beams P-R15, P-R25, and P-R40 (strengthened with CFRP plates), and beams F-R15, F-R25, and F-R40 (strengthened with CFRP fabrics) and subjected to repeated loads.

In Table 4, R15, R25, and R40 refer to the range of the repeated loads of magnitude 15, 25, and 40% of the ultimate strength of reference beams, respectively. It is observed that the plate reference beam had 59% higher strength than that of the unstrengthened beam. It is also observed that the repeated load test cycles have no significant effect on the load-carrying capacity of beams strengthened with CFRP. The repeated load cycles decreased the load-carrying capacity of beams strengthened with CFRP plates and fabrics by a maximum of 7.5 and 2.7%, respectively.

HIGH HUMIDITY REDUCES STRENGTH

The load-carrying capacity of beams strengthened with CFRP plates or fabrics is reduced after long-term exposure

to 100% humidity, dry heat, freezing and thawing, and thermal expansion environmental conditions. The most significant reduction (33%) in the ultimate load of strengthened beams is due to long-term exposure to 100% humidity. The onset of delamination was the primary mode of failure of strengthened beams with and without exposure to environmental conditions and repeated loads.

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