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Load–deflection behavior of RC beams strengthened with GFRP sheets subjected to different environmental conditions

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Abstract

An investigation to examine the durability of reinforced concrete beams strengthened with glass fiber reinforced polymer (GFRP) laminates is performed. A total of 84 beam specimens were prepared for this study. The performance of these specimens was assessed through evaluating the flexural capacity and load–deflection relationships of the beams after placing them in different environments directly or indirectly with simulated field condition for a specified period of time. The specimens were divided into six categories which include controlled laboratory environment (unexposed category), outside environment (direct exposure to hot–dry field conditions), wet–dry normal water environment, wet–dry saline (NaCl) water environment, and wet–dry alkaline (NaOH) environment. Each category consisted of unstrengthened and strengthened beams. Furthermore, some of the specimens of the hot–dry field exposure were coated with protection paint against ultra violet (UV) rays. The specimens of different wet–dry environments were exposed to a time cycle of two weeks inside the solution and two weeks outside the solution. The test results carried out after 6, 12 and 24 months of exposure to different environmental conditions, show that none of the aforesaid environmental conditions have a noticeable influence on the flexural strength of the beams.

Keywords: Durability; Environmental exposure; Flexure; GFRP; Long-term; Retrofit; Strengthening

1. Introduction

Fiber reinforced polymers (FRPs) in the form of sheets or plates can offer substantial economic advantages for the construction industry. Recent advances in FRPs suggest that they have enormous potential in future construction and repair applications. In the last decade, FRPs have found many applications in civil engineering industry. The growing demand for the use of FRPs with concrete beams, columns, walls, slabs, and pipes created a great need for understanding the short and long-term behavior of the composite system under different loading configurations and environmental conditions. The materials may undergo various service conditions which may include some real hostile conditions. For example, hot–wet weather, prolonged elevated temperature, sudden changes of ambient temperature and chemical corrosion. The composite adhesive and the adherent may undergo environmental degradation and the bond of the interface may be affected. This may, in turn, affect the performance and the long term durability of the composite system. Another reason for such debonding between composite and concrete is the thermal mismatch between the fibers and the matrix, which can setup compressive stresses in the fibers. The other reason is the ability of the composite to absorb moisture which may influence the integrity between the fibers and the matrix. A summary of the work that has been carried out to investigate the durability (the capacity to maintain visual and structural integrity with time in typical civil engineering environments) of composite material as an external strengthening material for concrete is presented next.

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2. Previous works on durability of FRP strengthened beams

Rostasy [1] conducted a recent assessment on the available experimental data [2–4] and revealed that GFRP behavior degrades when it is in permanent contact with dissolved alkaline solution of pH 13. A significant loss of tensile strength occurred within a short time (1000 h) of storage in NaOH (1 mol/l) and cementitious extract at 23 °C. Another test data on ARAMID FRPs (AFRPs) show that in alkaline solution of 20 °C, the strength can be reduced to between 55% and 60% of the unexposed strength. However, CFRP is durable in usual environments compared to GFRP and AFRP provided that they are protected against UV-light. Experimental study by Katsuki and Uomoto [5] demonstrated that GFRP bars in sodium hydroxide solution (1 mol/l) at 40 °C, strength looses 70% of their ultimate strength after 120 days. Degradation of FRP fabrics in acid and alkali solution at different temperatures was investigated by Uomoto and Nishimura [6]. The accelerated degradation test was carried out at 20 °C, 40 °C and 80 °C. They observed that Carbon fibers possess excellent chemical resistance and only 20% loss in tensile strength occurred at 80 °C in hydrochloric acid solution (1 mol/l) after 120 days. The worst case they found for Glass fibers when immersed in any of the solution at the temperature of 80 °C. The glass fibers showed, for example, 96% strength reduction in sodium hydroxide alkaline solution (1 mol/l) within 9 h only. In case of Aramid fiber of Technora type, the strength was reduced with the increase in immersion time and temperature. Strength was reduced by about 80% in hydrochloric acid and 45% in sodium hydroxide after 90 days. Furthermore, a study performed by Nguyen et al. [7] shows that water accumulated at the polymer/fiber interface results in substantial loss in the shear strength of epoxy/E-glass fiber composites. In a separate investigation by Pantuso et al. [8], tensile strength reduction of up to 7% and elastic modulus reduction of up to 10% were reported for glass fiber bars immersed in distilled water at 23 ± 2 °C within 60 days. Similarly Aramid (Kevlar) fibers are also affected by water mostly at high temperatures [9,10]. However, Carbon fiber experiences a small effect on the tensile strength due to water exposure [11,12].

The effect of different environmental conditions on reinforced concrete beams strengthened by FRP laminates was investigated by several researchers. For example, Chajes et al. [13] investigated RC beams (38 mm wide × 28.6 mm high × 330 mm long) in both wet–dry and freeze–thaw environments with AFRP, GFRP and CFRP fabrics bonded to the tension face of the beams. A wet–dry cycle was completed by immersing the beams in a 4% $CaCl_2$ solution for 18 h, followed by 8 h drying at room temperature. On the other hand, a freeze–thaw cycle involved immersing the samples in 4% $CaCl_2$ for 16 h in a freezer at −17 °C followed by 8 h of thawing at room temperature. The AFRP and GFRP strengthened beams lost 36% of the unexposed strength while CFRP strengthened beams lost 19% after 100 wet–dry cycles. The strength losses after 100 freeze–thaw cycles were observed to be 9%, 27% and 21% for the AFRP, GFRP and CFRP strengthened beams, respectively. This study indicates that the long-term performance of CFRP strengthened beams is better than AFRP and GFRP strengthened specimens. It also indicates that wet–dry environment yielded more degradation in the strength of beams than freeze–thaw environment.

Toutanji and Ortiz [14] tested concrete beams (50 mm × 50 mm × 300 mm) in wet–dry environment which were strengthened with GFRP and CFRP plates bonded to tension faces using different types of epoxy. A wet–dry cycle involved immersion of the samples in a 3.5% salt solution for 4 h followed by 2 h of drying at 35 °C and 90% relative humidity (RH). When tested in flexure after 300 wet–dry cycles, all the beams failed due to debonding of the FRP plates within 3–33% of the unexposed strength. However, the load and deflection for CFRP strengthened beams were higher than the GFRP strengthened beams. It was also reported in the study that the type of epoxy could be a critical factor on long-term durability of the strengthened beams.

Toutanji and El-Korchi [15] performed an experimental study on the tensile performance of cementitious specimen wrapped by Carbon (C1 and C2 type) and Glass (E-type) FRP tow sheets at different environmental exposures. Experimental results showed that no decrease in strength was observed for C1 carbon fiber wrapped specimens due to wet–dry or freeze–thaw exposure while C2 carbon fiber wrapped specimen experienced a 10% reduction in strength. On the other hand, Glass fiber wrapped specimen experienced 20% and 5% reduction in strength due to wet–dry and freeze–thaw exposure, respectively. Very recently, the short-term flexural performance of beams strengthened by CFRP strip were investigated by Nollet et al. [16] under room temperature (+25 °C) and freezing temperature (−25 °C). It was observed that due to freezing, both the load and deflection increased. A 35% increase in flexural capacity was noted under freezing temperature. In a separate study, freeze–thaw cycling effect on beams strengthened with CFRP sheets was studied by Arntsen and Pedersen [17]. Some specimens were moist-conditioned at 80% RH while the others were water-saturated before strengthening and subsequently sealed against evaporation. The beams were subjected to 56 cycles of freezing and thawing (−22 °C to +17 °C), each of which involved 24 h duration time (9 h and 15 h above and below 0 °C). The experimental results showed that the deviation between the load–deflection curves was negligible for different exposures such as no freeze–thaw with 80% RH, freeze–thaw with 80% RH and freeze–thaw with water saturated. In other words, the study indicated no significant effect of moisture condition or freeze–thaw action at all on the strengthened beams.

Javed [18] tested steel reinforced concrete beams externally bonded with carbon fiber tow sheets and found that beams aged under acidic and alkaline environments behaved differently from the five cycle hydrothermal aged beams, i.e., increasing stiffness over the control beams. Additional aging up to 15 cycles, led to a drop in stiffness of wrapped concrete beams to that of the control beams. Katsuki and Uomoto [5] performed durability study (under wet/dry cycles) on lap joint strength, adhesive strength, and bond strength of unidirectional fiber sheets bonded to concrete. They found no reduction in adhesive strength and lap joint strength, from the results of interface degradation of concrete and fiber sheets.

Green and Bisby [19] focused on freeze–thaw effects on bond between concrete and glass fiber sheets. At the end of 300 freeze–thaw cycles, the beams were tested to failure under 4 point bending. All beams failed under the same failure mode i.e., peeling of the bottom portion (about 1/4″ thickness) of concrete off the beam along with fiber sheets. It was concluded that freeze–thaw action did not cause any degradation to bond at the concrete/FRP interface, which was reinforced from a similar study by Tysl et al. [20].

Ekenel et al. [21] conducted an investigation to address the effect of surface moisture, relative humidity and temperature on the bond strength between concrete and CFRP reinforcement. Their test results revealed that high surface moisture content, extreme humidity and extreme low temperature can be detrimental to bond strength. To obtain desirable bond performance they also recommended a maximum allowable limit on surface moisture content, relative humidity and temperature at installation.

GangaRao and Barger [22] investigated more than 100 coupon level concrete specimens (cubes and beams) for bond strength evaluation between concrete and glass, or carbon fabric before and after aging them under acidic and alkaline solutions, and to temperature and humidity changes. Some of the coupons were aged with or without sustained stress. Conditioning duration varied between 1 and 9 months. At designated time intervals, the specimens were removed from the conditioning environment and tested. Strain gages were used to evaluate the rate of degradation as well as the strain distribution along the FRP composite strips. The author observed that the average variation in the bond strength of the specimens (glass and carbon) under accelerated aging were within 10% of unaged. Accelerated aging consisted of parameters such as pH change (3–13), temperature fluctuation (room temperature and freeze–thaw between 12 °F and 120 °F) and varied degree of sustained stress. It was also observed that the 20% sustained stress had no noticeable effect on bond strength of both carbon and glass fabric with concrete.

Almusallam et al. [23] investigated the performance of concrete cylinders wrapped with GFRP composite sheets subjected to different environment exposure conditions. The results showed that exposure to high temperature, outside environment and wet/dry conditions had a little effect on the compressive strength of specimens wrapped with GFRP sheets, specially when compared with the obtained values for samples kept in room temperature. The effect of alkaline solution environment was significant, specially for samples kept at elevated temperature, in which a high degradation occurred in the fiber composites themselves. Also the results showed that at the same stress level, the wrapped cylinders exhibited smaller lateral strain in comparison to the unwrapped cylinders, while the axial strains were higher than the lateral strains at any considered stress level for all wrapped and unwrapped cylinders.

Almusallam and Al-Salloum [24] investigated the effect of different local environmental conditions on the long-term behavior of GFRP bars in concrete beams subjected to sustained loads. This was achieved through testing concrete beams reinforced with GFRP bars and subjected to a certain stress level. All beams were either completely or partially immersed in different environments (tap-water and sea-water) at elevated temperature. Test results are expressed in terms of tensile strength of GFRP bars and load–deflection behavior of both unstressed and stressed beams. The results show that there is significant loss in tensile strength of GFRP bars when subjected to sustained stress for the considered exposure conditions.

Grace and Grace [25] studied the durability of the reinforced concrete beams externally strengthened with CFRP plates and fabrics under adverse environmental conditions such as 100% humidity, salt-water, alkali solution, freeze–thaw thermal expansion, and dry-heat. They observed that the long-term exposure to humidity was the most-detrimental factor affecting the bond strength between CFRP plates/fabrics and RC beams. Beams strengthened with CFRP plates and exposed to 10,000 h of 100% humidity (at 38 ± 2 °C) experienced an average of 33% reduction in their strength.

Myers et al. [26] conducted an experimental program to investigate the durability of bond between concrete and various FRP sheets (Carbon, Glass, Aramid). The entire experimental program consisted of tests on 48 pre-cracked beam specimens strengthened in flexure with carbon, glass or aramid FRP sheets. The beams were pre-cracked under single point loading by applying the cracking load prior to strengthening with FRP sheets. After the beams were strengthened with the FRP sheets, they were subjected to combined environmental effects including freeze-and-thaw, high moisture, high temperature cycling and indirect ultraviolet radiation exposure under sustained load (0%, 25% and 40% of ultimate load). The results showed that the combined environmental exposure has an adverse effect on the bond performance of FRP sheets to concrete. Members strengthened with three different FRP sheets indicated a reduction in flexural stiffness of the member through the degradation of bond of FRP sheet with concrete. It was also concluded that; specimens conditioned under higher sustained loads (40% of ultimate load) comparatively degrade more in bond when compared to unloaded specimens.

Ren et al. [27] performed freeze–thaw tests on concrete structures strengthened with FRP sheets and concluded that the bond strength between concrete and FRP sheets decreases under the freeze–thaw cycles.

Leung et al. [28] investigated the flexural capacity of strengthened concrete beams exposed to different environmental conditions. They used 80 plain concrete beams strengthened with mild steel or carbon fiber reinforced polymer plates. Specimens were kept under water at 27 °C for 28 and 60 days. In this investigation, it was proved that strengthening with CFRP provides greater enhancement than strengthening with steel plates. Exposure to water for long periods caused change of the load-carrying capacity as well as the midspan deflection.

3. Research significance

It appears that the test results by Arntsen and Pedersen [17] and GangaRao and Barger [22] did not agree with the general durability effect of moisture condition and freeze–thaw action as noted by other researchers [13–15]. However, the general trend of these environmental exposures is to degrade the flexural or tensile performance and GFRP composite strengthened specimens are more vulnerable to the environmental exposures. It also appears that the behavior of strengthened beams was mostly investigated to explore short-term durability effect and in freezing or room temperature environment like cold or normal regions of the world. Hence further studies on the durability performance of FRP strengthened beams under long-term periods are necessary. Moreover, the long-term durability study in arid region particularly under hot climate is not conducted yet.

In this study, the long-term durability performance of GFRP strengthened beams was investigated for both hot–dry and wet–dry climates as experienced in the arid region like the central province of Saudi Arabia. The environmental exposures considered in the investigation include wet/dry cycles in salt water, wet/dry cycles in alkaline water, wet/dry cycles in normal water, and direct and indirect exposure to sunlight.

4. Experimental program

The purpose of this study is to investigate the durability of beams strengthened with GFRP sheets by evaluating flexural capacity of these specimens after placing them in different environmental conditions including the harsh weather (field condition of Riyadh) for 24 months. *Eighty-four* specimens were prepared for this purpose. Details of the environmental conditions along with the test results are reported next.

4.1. Environmental exposures

A total of 84 specimens were prepared to investigate the durability of beams strengthened with GFRP sheets as listed in Table 1. Table 1 shows the exposure category, number of specimens used for conducting tests in each group; strengthening status; ultraviolet (UV) paint status i.e. whether UV paint was used or not and age of specimens at the time of testing. The concentrations of acidic and alkaline solutions are also mentioned in this table. To simulate the worst alkaline environment pH value of 13–14 was maintained for durability study in the alkaline environment. The durability performance was determined by evaluating flexural capacity of these specimens after placing them in different environments directly or indirectly with simulated field condition for a specified period. *Eighteen* specimens were exposed to actual field environment, and the remaining 66 specimens were exposed to different environments within the laboratory.

4.1.1. Field exposure

Eighteen specimens were subjected to outside field conditions (hot–dry field conditions). All the 18 specimens were strengthened with one layer of GFRP sheet. Nine of these specimens were exposed to field conditions without any protection against UV rays and the other nine specimens were coated with a lineal polyurethane paint for UV protection and with high quality finish. Furthermore, all the 18 specimens were subjected to direct exposure to sunlight. The specimens were tested after 6, 12 and 24 months of exposure to the above environmental conditions. The specimens which were exposed for 6 months, they were exposed during the months of April to September. The field conditions in Riyadh around the year are presented in Table 2.

4.1.2. Laboratory exposure

The Laboratory exposure specimens were divided into four categories (Table 1). They are laboratory control specimens (unexposed category), wet–dry normal water specimens, wet–dry saline (NaCl) water specimens, wet–dry alkaline (NaOH) specimens at normal temperature 23 ± 2 °C. Each category consisted of unstrengthened and strengthened beams.

Twelve specimens were kept in the laboratory as control specimens for testing after 6 and 12 month periods (for each age three specimens were strengthened with the GFRP sheet whereas three were not strengthened). The normal temperature of the laboratory was 23 ± 2 °C.

The specimens of different wet–dry environments were exposed to a time cycle of 2 weeks inside the solution and 2 weeks outside the solution. For each category, the specimens were scheduled for flexural test at 6, 12 and 24 months. Effects of environmental and climatic conditions were studied both for unstrengthened and strengthened specimens.

4.2. Specimen details

All beams had a 150 mm × 150 mm cross-section, reinforced with 2 ∅10 mm diameter steel bars at an effective depth of 110 mm. They were provided with ∅6 mm diameter steel stirrups at 60 mm center to center spacing and

Table 1
Testing program for durability of GFRP strengthened beams

Exposure category	Number of specimens	Strengthening status	UV paint status	Age at testing (months)
Laboratory exposure				
Control (room temperature 23 ± 2 °C)	3	Unstrengthened	–	6
	3	Strengthened	–	6
	3	Unstrengthened	–	12
	3	Strengthened	–	12
Wet–dry (water) (23 ± 2 °C)	3	Unstrengthened	–	6
	3	Strengthened	–	6
	3	Unstrengthened	–	12
	3	Strengthened	–	12
	3	Unstrengthened	–	24
	3	Strengthened	–	24
Wet–dry (NaCl) 5% or 5 g/l (23 ± 2 °C)	3	Unstrengthened	–	6
	3	Strengthened	–	6
	3	Unstrengthened	–	12
	3	Strengthened	–	12
	3	Unstrengthened	–	24
	3	Strengthened	–	24
Wet–dry (NaOH) pH 13–14 15 g/l (23 ± 2 °C)	3	Unstrengthened	–	6
	3	Strengthened	–	6
	3	Unstrengthened	–	12
	3	Strengthened	–	12
	3	Unstrengthened	–	24
	3	Strengthened	–	24
Field exposure				
Field exposure (outside the laboratory)	3	Strengthened	Unpainted	6
	3	Strengthened	Painted	6
	3	Strengthened	Unpainted	12
	3	Strengthened	Painted	12
	3	Strengthened	Unpainted	24
	3	Strengthened	Painted	24
Total	84			

Table 2
Average Riyadh monthly dry bulb temperature (DBT) and relative humidity (RH) around the year

Month	DBT Min. °C	DBT Max. °C	RH Mean %
January	8.79	19.58	57.22
February	11.40	22.04	46.74
March	13.86	24.49	47.23
April	18.28	29.93	39.28
May	23.98	37.53	17.21
June	26.35	40.30	11.30
July	28.09	41.28	11.21
August	27.52	41.93	11.50
September	23.28	38.04	14.79
October	19.44	33.65	20.98
November	13.17	25.37	35.41
December	10.21	19.80	62.05

distributed over a simply supported span of 1200 mm. The beams were loaded by two concentrated loads that were placed at a distance 75 mm on either side of mid-span. The beams were designed to fail in flexure. Further details of the cross-section of the beams and the test set-up are shown in Figs. 1 and 2, respectively.

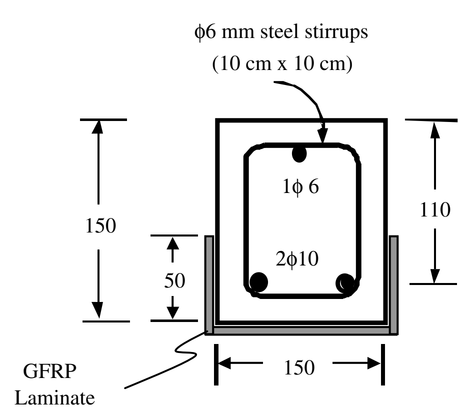

Fig. 1. The beam cross-section (dimensions are in mm).

4.3. Material properties

The mix proportions used to cast all beams were 1:1.42:0.71:1.42 (cement:sand:10 mm maximum size aggregate:20 mm maximum size aggregate) with a water/cement ratio of 0.50. The average yield stresses of steel bars were 500 MPa and 324 MPa for ∅10 and ∅6 mm, respectively,

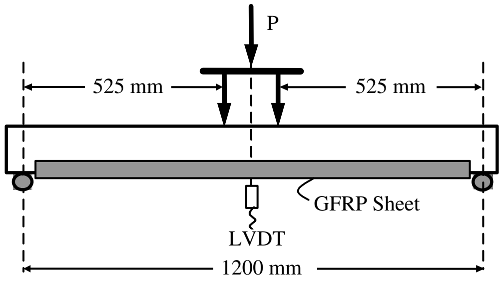

Fig. 2. The beam set-up.

with an elastic modulus of 200 GPa. The average 28-day compressive strength of concrete was 36.4 MPa. One type of GFRP sheet was used: a uni-directional GFRP with the fibers oriented in longitudinal direction. The fiber-composite material consisted of glass fiber bonded together with an epoxy matrix. The ultimate strength and the elastic modulus of the GFRP composite were 510 MPa and 23,400 MPa, respectively.

4.4. Preparation of test specimens

All the beams were cast outside the laboratory, covered with burlap, demolded approximately 24 h after casting. Then, they were stored inside the laboratory, subjected to 14 days of intermittent curing (twice a day) and left to air drying until the day of strengthening. It is worth to mention, although all the 84 beams were not cast from the same batch but same conditions were strictly maintained during the preparation of batches and casting of beams.

One layer of GFRP sheet was bonded to the tension face of the beam specimen. In order to increase the anchorage and avoid debonding of GFRP sheets during testing, they were attached in a U-shape with 50 mm extension on the sides of the beam as shown in Fig. 1. It was observed, through all the performed tests that this U-shape wrapping works effectively in preventing the debonding of GFRP sheets. Before applying the epoxy, the concrete surface was machine sand-blasted then cleaned to ensure a good bond between the epoxy glue and the concrete surface. The epoxy was machined-mixed and hand-applied. A special tool with a groove of 1 mm was used to maintain a thickness of 1 mm during the placement of GFRP sheets. The bond thickness was not specifically controlled, but the excess epoxy was squeezed out along the edges of the sheet, assuming complete epoxy coverage.

The specimens were instrumented with LVDT's. One LVDT was placed at the midspan to determine the deflection of the beam. All specimens were loaded up to failure with the same loading rate. During testing, load and deflection were recorded by an automatic data acquisition system.

5. Results and discussion

After instrumentation, all the beams were subjected to two-point loading system to determine deflections and ultimate failure loads with and without exposure to the different environmental conditions. The test results in the form of load–deflection behavior are presented in Figs. 3–7. To facilitate the comparison between the test results for different beams, the same scale was used in all figures. It is to be noted that for every group of specimens, curves for all the specimens are not plotted and only a representative curve for every group is shown. This is in order to avoid cumbersome presentation. Out of a group of three curves that curve is chosen as representative curve which is close to

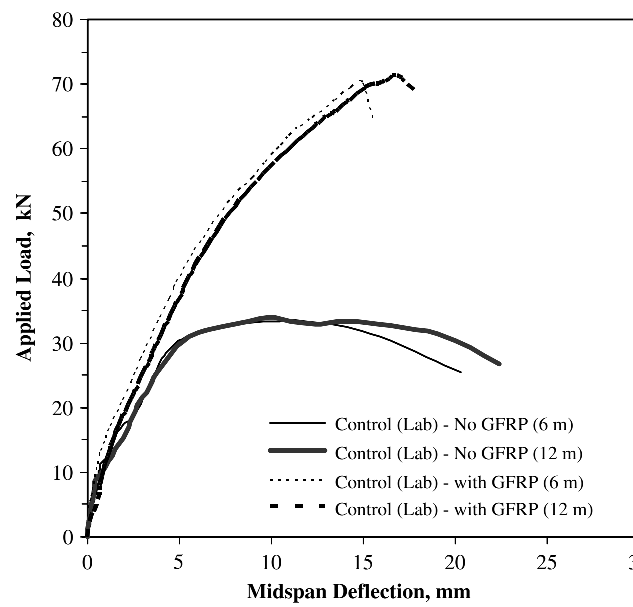

Fig. 3. Load–deflection relationship for the laboratory control beams.

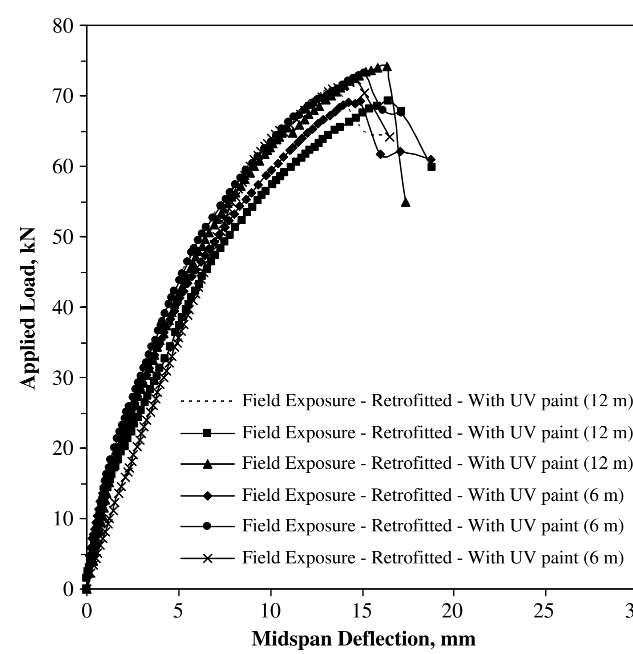

Fig. 4a. Load–deflection relationship for two groups of strengthened specimens subjected to hot–dry field conditions.

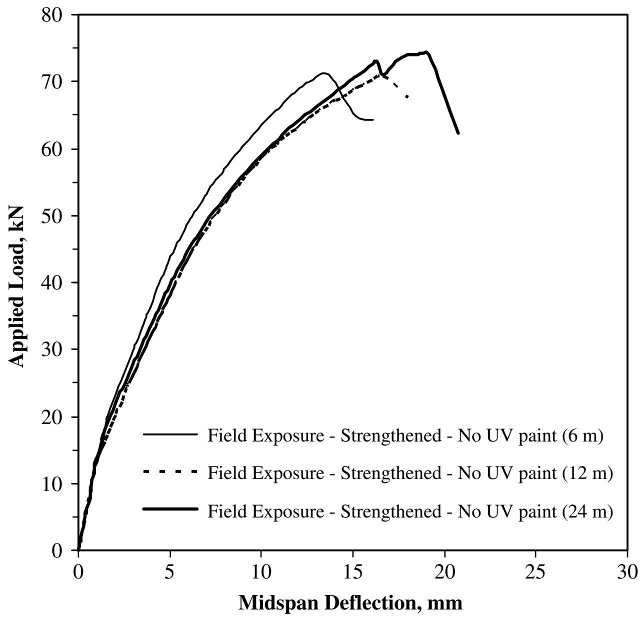

Fig. 4b. Load–deflection relationship for strengthened beams subjected to hot–dry field conditions without UV protection painting.

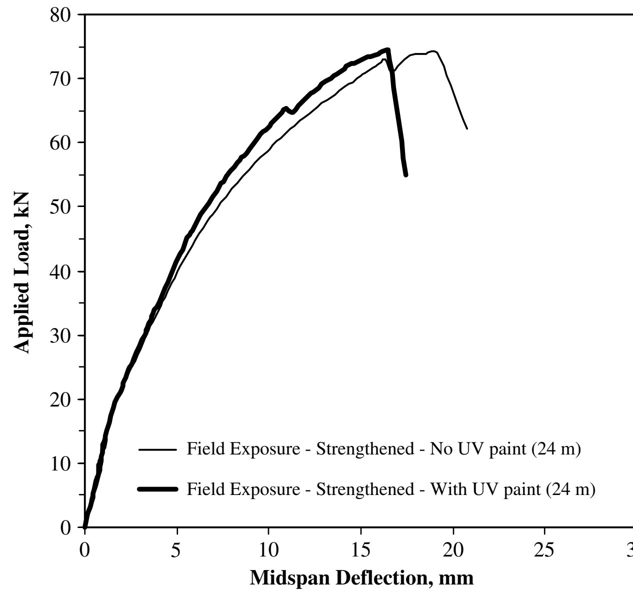

Fig. 6. Load–deflection relationship for strengthened beams subjected to hot–dry field conditions for 24 months with and without UV protection painting.

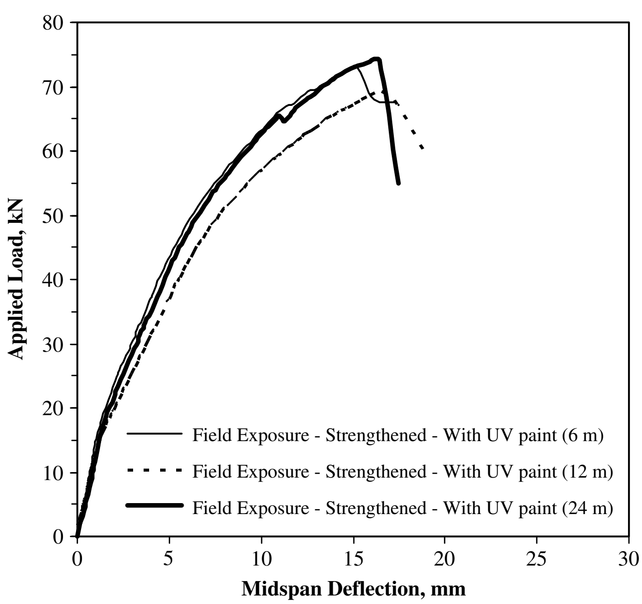

Fig. 5. Load–deflection relationship for strengthened beams subjected to hot–dry field conditions with UV protection painting.

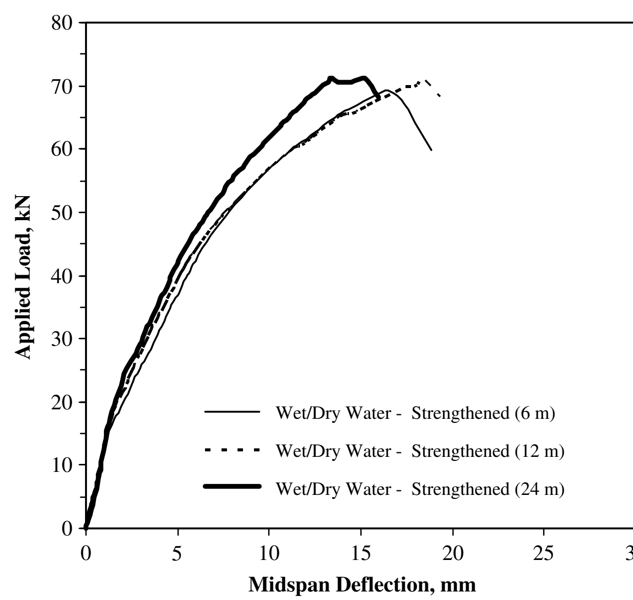

Fig. 7. Load–deflection relationship for strengthened beams subjected to wet–dry water cycles.

the average one i.e. lies best between the curves of other two specimens. However, in order to justify, curves of 6 m and 12 m specimens are shown in Fig. 4a. This figure clearly indicates, if instead of plotting the representative curve, curves of all the specimens are plotted, plot will be very much clumsy and it would be difficult to compare response of one group of specimens with other.

Fig. 3 shows the relationship between the vertical deflection at the beam midspan and applied load for strengthened and unstrengthened specimens placed in the laboratory, tested at 6 and 12 months of age. The results clearly show that there is about 100% gain in the flexural strength of the beams as a result of attaching one layer of the GFRP sheet to the tension side of the beam. However, it is to be noted that, since in the present study a very small steel reinforcement ratio is maintained, strength gain due to GFRP sheet has reached to this very high value. For higher steel reinforcement ratios, the gain in strength may not be so high. The results presented in Fig. 3 also show that at later stages of loading (e.g. beyond 30 kN) stiffness of the beam was also greatly enhanced due to the strengthening with the GFRP sheet.

Figs. 4b and 5 present the load–deflection relationships for the specimens exposed to field conditions (hot–dry field conditions) without and with UV coating, respectively. In order to visualize the effect of exposure period on the durability of GFRP sheets, the results presented in Fig. 4 clearly reveal that due to the 6, 12 and 24 months of exposure period, the solar radiation did not cause any noticeable deterioration (with time) in the GFRP sheet without UV protection paint. The same behavior was observed for those beams strengthened with GFRP sheets with UV protection paint as shown in Fig. 5. Furthermore, the load–deflection relationships for the specimens exposed to field conditions (hot–dry field conditions) with and without UV coating for 24 months are shown in Fig. 6. The results in Fig. 6 show that the load–deflection curves for the specimens exposed to field conditions with or without UV protection paint are almost the same. However, the degradation effect of solar radiations (particularly of UV rays) cannot be denied if the GFRP sheets are exposed to such radiations for long time (e.g. number of years). Moreover, Figs. 4, 5, 7 and 9 reveal that for 24 month exposed specimens there is less degradation than 12 month exposed specimens. This is due to the fact that for 24 month specimens, in their last 12 months, gain of strength with time was more than loss of strength due to FRP degradation and environmental effects on concrete.

The resistance to UV deterioration may be attributed to the quality of the epoxy used in this study to attach the sheets to the beams, which may have covered the sheets against the negative effect of the weather. Thus, they acted as a barrier between the GFRP and the environment. However, further studies should be conducted to investigate whether this barrier effect of the epoxy would hold under service load conditions or not.

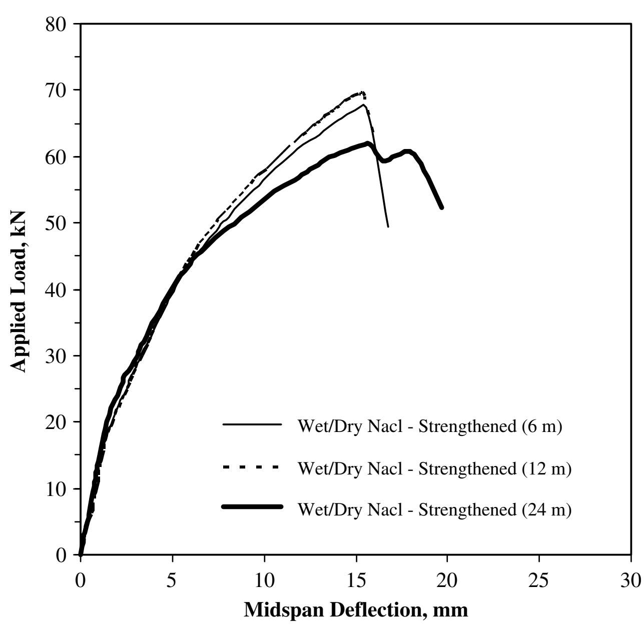

Fig. 8. Load–deflection relationship for strengthened beams subjected to wet–dry NaCl cycles.

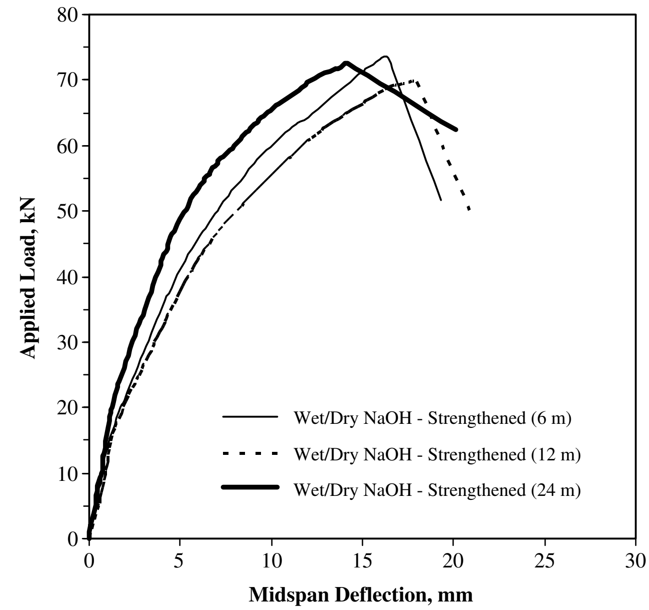

Fig. 9. Load–deflection relationship for strengthened beams subjected to wet–dry NaOH cycles.

Furthermore, Fig. 8 shows that 24 month specimen suffers some degradation in comparison to 6 and 12 month specimens. This can be attributed to little higher deterioration in the FRP system, in its last 12 months, in a wet–dry NaCl environment.

Table 3 summarizes the statistics of peak load and ultimate displacement for each group of specimens. A comparison of average peak load for strengthened specimens with unstrengthened specimens, in general, shows that GFRP sheets increases the strength of the beam substantially (for most of the specimens above 100%). Further, the table also shows that effect of environmental changes to average peak load is insignificant on strengthened specimens. This again shows sound durability of GFRP sheets. The coefficient of variation (COV), a measure of dispersion, of various group shows that, both the peak load and ultimate displacement variation among the specimens is significantly small.

It is worth mentioning here that some of the previous works [13–15] showed a noticeable ratio of degradation of different types of GFRP materials although the period of exposure, under some environmental conditions similar to those considered in this study, was much less than six months. This may be attributed, as indicated earlier, to the quality of the epoxy used to attach the laminates to the beams, which may have acted as a barrier between the GFRP and the environment. Other factors such as concrete quality, type of GFRP and exposure fluid concentration and its temperature may also play a major role in the degradation rate.

Table 3
Statistical results of GFRP strengthened beams

Exposure category	Number of specimens	Strengthening status	Age at testing (months)	Peak load		Ultimate displacement	
				Mean (kN)	COV	Mean (mm)	COV
Laboratory exposure							
Control (room temperature 23 ± 2 °C)	3	U	6	33.8	0.01	20.3	0.07
	3	S	6	70.3	0.03	15.5	0.10
	3	U	12	33.4	0.09	22.4	0.09
	3	S	12	71.3	0.07	18.3	0.06
Wet–dry (water) (23 ± 2 °C)	3	U	6	30.7	0.03	20.9	0.03
	3	S	6	69.2	0.04	18.9	0.07
	3	U	12	30.8	0.05	21.5	0.08
	3	S	12	70.7	0.01	19.3	0.10
	3	U	24	32.1	0.01	17.1	0.06
	3	S	24	71.2	0.03	15.9	0.09
Wet–dry (NaCl) 5% or 5 g/l (23 ± 2 °C)	3	U	6	33.6	0.05	21.8	0.03
	3	S	6	67.5	0.10	16.7	0.06
	3	U	12	30.7	0.05	21.5	0.10
	3	S	12	69.4	0.06	15.9	0.07
	3	U	24	32.4	0.07	20.1	0.07
	3	S	24	61.8	0.05	19.7	0.06
Wet–dry (NaOH) pH 13–14 15 g/l (23 ± 2 °C)	3	U	6	30.7	0.01	20.2	0.03
	3	S	6	73.4	0.02	19.3	0.09
	3	U	12	33.1	0.01	18.6	0.06
	3	S	12	69.7	0.08	20.9	0.06
	3	U	24	33.1	0.01	19.1	0.05
	3	S	24	72.5	0.07	20.2	0.10
Field exposure							
Field exposure (outside the laboratory)	3	SU	6	71.2	0.01	16.1	0.16
	3	SP	6	73.3	0.04	17.2	0.06
	3	SU	12	70.4	0.03	17.9	0.08
	3	SP	12	69.2	0.05	18.9	0.06
	3	SU	24	73.9	0.04	20.8	0.05
	3	SP	24	74.2	0.03	17.4	0.09
Total	84						

S, strengthened; U, unstrengthened; SU, strengthened and unpainted with UV paint; SP, strengthened and painted with UV paint; COV, coefficient of variation.

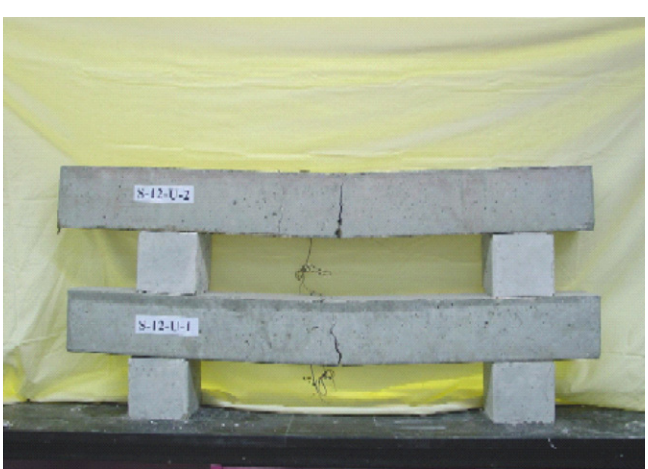

Fig. 10. Typical failure pattern of control (unstrengthened) beams.

Fig. 11. Typical failure pattern of one of the strengthened beams in wet–dry alkaline environment.

Typical flexure failure for all unstrengthened and strengthened beams was exhibited without any debonding of GFRP sheets. Figs. 10 and 11 show typical photos of failed unstrengthened and strengthened beams. Fig. 10 clearly shows, as cracks are almost vertical, the failures of beams are in flexure. Fig. 11 reveals that there is some partial detachment of concrete along with FRP sheet. This illustrates cohesive failure of concrete. In this failure, concrete lost its cohesion and part of the concrete detached from the main mass with externally bonded FRP sheet. However, no debonding was observed between concrete and FRP sheet.

6. Conclusions

The results of experiments performed on GFRP strengthened beams, establishes the sound durability of GFRP sheets in varied environmental conditions. It was observed that GFRP sheets attached to the beams and exposed to different curing conditions (NaOH, NaCl, and tap water) for a period of 6–24 months shows no degradation in imparting the strength and stiffness to strengthened beams. Effect of UV rays was also studied on the durability of GFRP sheets by exposing UV painted and unpainted strengthened specimens to solar radiations for 6–24 months. Again, no degradation in the performance of GFRP sheets was observed due to exposure to solar radiations (containing UV rays). However, the degradation effect of solar radiations (particularly of UV rays) cannot be denied if the GFRP sheets are exposed to such radiations for long time (e.g. number of years).

In addition to durability, results of present study also establish the effectiveness of GFRP sheets in upgrading the reinforced concrete beams. The results of FRP strengthened specimens, in general, showed that FRP sheets increase the flexural strength and ductility of RC beams to a great extent.

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