ELSEVIER

Cement and Concrete Composites **19** (1997) 351–358

0958-9465/97/$17.00

PII:S0958-9465(97)00028-0

Durability Characteristics of Concrete Beams Externally Bonded with FRP Composite Sheets

Houssam A. Toutanji[a] & William Gómez[b]

[a]Department of Civil and Environmental Engineering, University of Alabama in Huntsville, Huntsville, AL 35899, USA
[b]University of Puerto Rico, Department of Civil Engineering, Mayaguez, PR 00681-5000, Puerto Rico

(Received 6 February 1997; accepted 18 July 1997)

Abstract

The strengthening of concrete structures in situ with externally bonded fiber reinforced plastic (FRP) composite sheets is increasingly being used for repair and rehabilitation of existing structures. This paper provides information in the area of long-term durability of concrete beams externally bonded with FRP sheets. It was intended to study the effect of harsh environmental conditions such as wet/dry cycling using salt water on the performance of FRP-bonded concrete beams and on the interfacial bond between the fiber and the concrete. Concrete beams were strengthened with four different types of FRP sheet: two carbon and two glass. Three different types of two-part epoxy were used. Test variables included (1) the type of fiber, (2) the type of epoxy system, and (3) the environmental exposure condition. The specimens were conditioned in two different environments: (a) room temperature (+20°C), and (b) 300 wet/dry cycles (salt water was used for the wet cycles and hot air at 35°C and 90% humidity for the dry). At the end of each exposure, load–deflection curves of the specimens were obtained in order to evaluate their maximum capacity, stiffness, and ductility. The performance of the wet/dry exposed specimens was compared with those kept at room temperature.

Results showed that specimens subjected to wet/dry environmental conditions and those kept at room temperature exhibited significant improvement in flexural strength when FRP sheets were bonded to the tension face of the concrete beams. However, the specimens subjected to wet/dry conditions showed less improvement than those kept at room temperature. None of the specimens failed due to FRP rupture but rather due to the debonding between the FRP sheet and the concrete interface. The selection of epoxy was shown to be very important for using the FRP strengthening technique, especially in a marine environment.

Keywords: Beams, durability, epoxy, glass fiber, carbon fiber, reinforced plastic, flexural load, salt water.

INTRODUCTION

The rapid deterioration of older structures, which is caused by loss of material properties, exposure to severe climate, or increase in traffic loads in the case of bridges, demands the invention of new methods and materials for rehabilitation. Strengthening of structurally damaged concrete members has been accomplished so far by externally post-tensioning or by bonding thin steel sheets to the tension face. While external post-tensioning involves the use of complex anchoring devices, the corrosion of steel plates has been found to cause deterioration of the bond at a glued steel–concrete interface, rendering the structure vulnerable to overload and possible failure.

Fiber composites offer unique advantages for solving many civil engineering problems in areas where conventional materials fail to provide satisfactory service life. Fiber-reinforced plastic (FRP) composites possess excellent properties, such as high tensile strength and stiffness, light weight, and resistance to corrosion and chemicals. These properties make them particularly suitable for rehabilitation. Their lower density is important not only because it adds less weight to the existing structures, but also because of its greater convenience during construction. A number of researchers have conducted experimental and analytical investigations on the strength and stiffness of beams that are bonded with FRP composites.[1–9] Most have shown that beams strengthened with FRP fabrics exhibit much higher ultimate strength and deflection than reference beams.

The effect of acidic and alkaline conditioning under varying and constant temperature on strength and stiffness of concrete beams wrapped with carbon fiber sheets was studied.[10] Results showed that the bond shear strength of samples exposed to environmental conditioning decreased with respect to unconditioned samples. The percentage decrease was 17% for samples in acidic condition, 24% for samples in alkaline condition, and 29% for samples exposed to hygrothermal condition. In a different study, specimens made of a carbon FRP grid and a glass–carbon FRP grid with junctions at 100 mm (4 in) spacing were exposed for up to a year to solutions of salt and alkali, UV radiation with wet/dry cycling, and freeze–thaw action.[11] The tensile strength of these specimens was found to remain unaffected by the environmental conditions, whereas the junction strength was found to be sensitive to salt, alkali, and freeze–thaw action.

The purpose of the research presented in this paper is to provide information in the area of long-term durability of concrete beams externally bonded with FRP tow sheets. This research was intended to study the effect of harsh environmental conditions such as wet/dry cycling using salt water on the performance of FRP-bonded concrete beams and on the interfacial bond between the fiber and the concrete. Although small size specimens (laboratory size) were used in this research, the results can provide a better understanding of the effectiveness of different adhesives under severe environ-

Table 1. Mechanical properties of FRP sheets

FRP sheet	*Tensile strength (MPa)*	*E (GPa)*	*Ultimate strain (%)*	*Thickness (mm)*
C1	3485	228	1.5	0.165
C2	2940	373	0.8	0.165
G1	1518	69	2.1	0.118
G2	2270	72	3.2	1.30

Table 2. Mechanical properties of adhesive

Properties	*Epoxy Type I*	*Epoxy Type II*	*Epoxy Type III*
Chemical name	Modified amine/epoxy resin blend	Polyoxypropylenediamine hardener/epoxy resin	Amine saturant/solvent-free epoxy
Chemical composition	Modified amine 30% Alkyl ether amine 40%	Proprietary	Bisphenol A epoxy resin 50% Polyoxypropylenediamine 25% Isophorne diamine 15% Aliphatic amine 10%
Mixing proportion	1:2	3:7	1:2
Water miscibility	> 10%/ < 0.1%	> 10%/negligible	> 10%/insoluble
Density (g/cm^3)	1.1	1.11	N/A
Viscosity @ 25°C (cPs)	12350	9415	18000
Tensile strength (MPa)	55.9	69.7	54
Flexural strength (MPa)	78.7	79.4	69
Tensile modulus (GPa)	2.35	3.06	2.3
Elongation (%)	2.4	3.5–5.0	2.68

mental conditions. The results can also be used as preliminary data for the selection of a suitable epoxy system. Three different adhesives were used to study the influence of the two-part epoxy systems on the ultimate load capacity and ductility at room temperature and wet/dry conditions. The performance of the conditioned samples was compared with that of unconditioned samples (room temperature). This work can be an important step forwards for the development of design guidelines for the applications of FRPs in strengthening and repair.

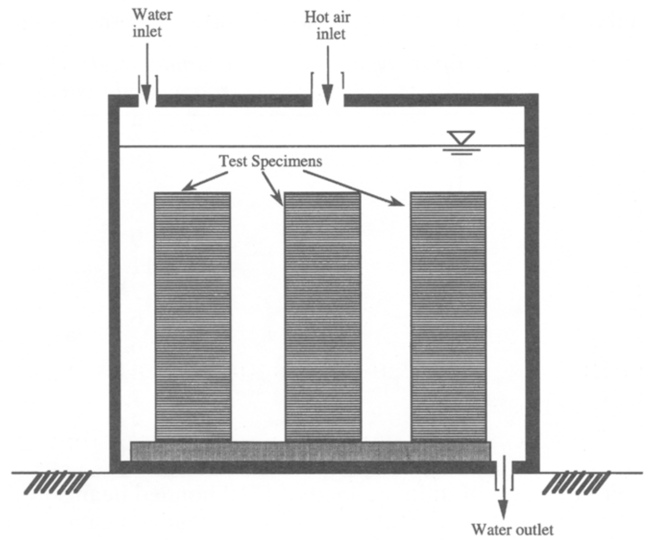


Fig. 1. Schematic of the wet–dry exposure set-up.

EXPERIMENTAL PROCEDURE

Materials

Small beams measuring 51×51 mm^2 and with a total length of 356 mm were constructed. Normal-strength concrete was used for the beams. The mix proportion of the concrete mix of cement:sand:gravel:water was 1:2:3:0.5. ASTM Type II Portland cement was used. The aggregate consisted of crushed stone of coarse aggregate with a maximum size of 12.7 mm, and concrete sand of fine aggregate. Four 100×200 mm^2 concrete cylinders were cast and tested to determine the mechanical properties of hardened concrete. The average 28 day compressive and flexural strengths were 30 MPa and 4.6 MPa respectively. The concrete sand material composition was made of 50% river and 50% beach sand. All specimens were moist cured at least 28 days before they were externally bonded with FRP sheets.

Four types of FRP composite material were used: two carbon (C1 and C2) and two glass (G1 and G2). A summary of the properties of the FRP sheets is presented in Table 1. Three different two-part epoxy systems were used: I, II, and III. A summary of the properties of the epoxies is presented in Table 2.

Specimen preparation

A total of 56 conditioned beams were tested. Half the beams were exposed to wet/dry cycling in the environmental chamber and the other half were kept at a constant room temperature. Four unwrapped beams were exposed to wet/dry cycling and four were kept in room temperature. Before bonding the FRP sheets to the tension side, the concrete surface was smoothened, cleaned, and completely dried before the epoxy was applied. Two-part primer was hand-mixed for at least 5 min and applied on the concrete surface. After the primer was tack-free, the two-part epoxy was mixed thoroughly for 5 min and was applied on the surface and then the FRP sheet was laid on it. A uniform pressure was applied on it to remove the entrapped air. The epoxy was allowed to cure for at least 30 min and then a thin overcoat layer of epoxy was applied on the FRP sheets. All specimens were externally bonded with one layer of FRP sheets on the tension sides of the beams. Bond thickness was controlled by using 250 g/m^2 of primer and 400 g/m^2 of epoxy undercoat and 200 g/m^2 of epoxy overcoat. All specimens were left at room temperature for at least 3 days before exposure to ensure the complete curing of the epoxy.

Half of the 56 specimens were left at room temperature for 75 days. These specimens were used as control tests. The other half were placed in a specially constructed environmental chamber and were exposed to 300 cycles of wetting and drying. The wet/dry environmental chamber is shown schematically in Fig. 1. The specimens were subjected to salt environments

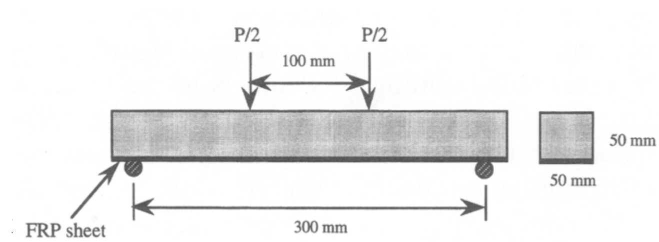


Fig. 2. Four-point bend test.

Table 3. Experimental results and notation of the tested beams

Beam	*Epoxy type*	*Ultimate load (kN) (room conditioning)*	*Fr*/Fr*[a]	*Ultimate load (kN) (wet/dry conditioning)*	*Fr*/Fr*[b]
000	—	2.2	—	2.7	—
C1I	I	8.0	3.7	6.7	2.5
C1II	II	8.7	4.0	9.6	3.6
C1III	III	6.8	3.1	7.8	2.9
C2I	I	9.8	4.5	8.9	3.3
C2II	II	11.3	5.1	12.0	4.4
C2III	III	7.9	3.6	9.0	3.3
G1I	I	6.3	2.9	5.5	2.1
G1II	II	6.5	3.0	6.1	2.3
G1III	III	4.8	2.2	5.8	2.1
G2I	I	7.7	3.5	7.7	2.9
G2II	II	8.9	4.1	9.9	3.7
G2III	III	8.0	3.6	9.2	3.4

[a] Fr*/Fr: ratio of ultimate load of FRP bonded beams to that of unbonded at room temperature.
[b] Fr*/Fr: ratio of ultimate load of FRP bonded beams to that of unbonded under wet/dry conditions.

in which there were alternating wet and dry cycles (hot air at 35°C average and 90% humidity). Sea water was simulated using 35 g of salt in 1 liter of water. This is the approximate content of salt found in the ocean. The duration of the wet cycle was 4 h, and that of the dry cycle 2 h. Thus, the specimens were exposed for a total of 75 days. At the end of 300 cycles, the load deflection behavior of the samples was obtained to evaluate their strength, stiffness, and ductility, which were compared to corresponding values obtained from the control samples (samples kept at room temperature).

The specimens were tested in flexure, under a four-point bend load. The test set-up is shown schematically in Fig. 2. The four-point bend tests were conducted using an Instron® testing machine. The specimens were loaded to failure at a cross-head speed of 0.2 mm/min. Load and deflection were recorded digitally by an automatic data acquisition system.

RESULTS AND DISCUSSION

Room temperature exposure

Experimental results for all specimens conditioned in room temperature and in wet/dry environments are presented in Table 3. The ultimate flexural load was increased significantly by externally bonding FRP sheets to the tension face of concrete beams. The ratio of the ultimate flexural load of strengthened beams to unstrengthened beams, under room temperature conditions, was between 2.2 and 5.1, depending on the type of FRP sheet and the type of epoxy resin system. Results show that epoxy II always produced higher strength than epoxies I or III. However, regardless of the epoxy system, specimens strengthened with carbon fiber performed better than those strengthened with glass fiber; also, C2 fiber performed better than C1, and G2 fiber performed better than G1, as seen in Table 3.

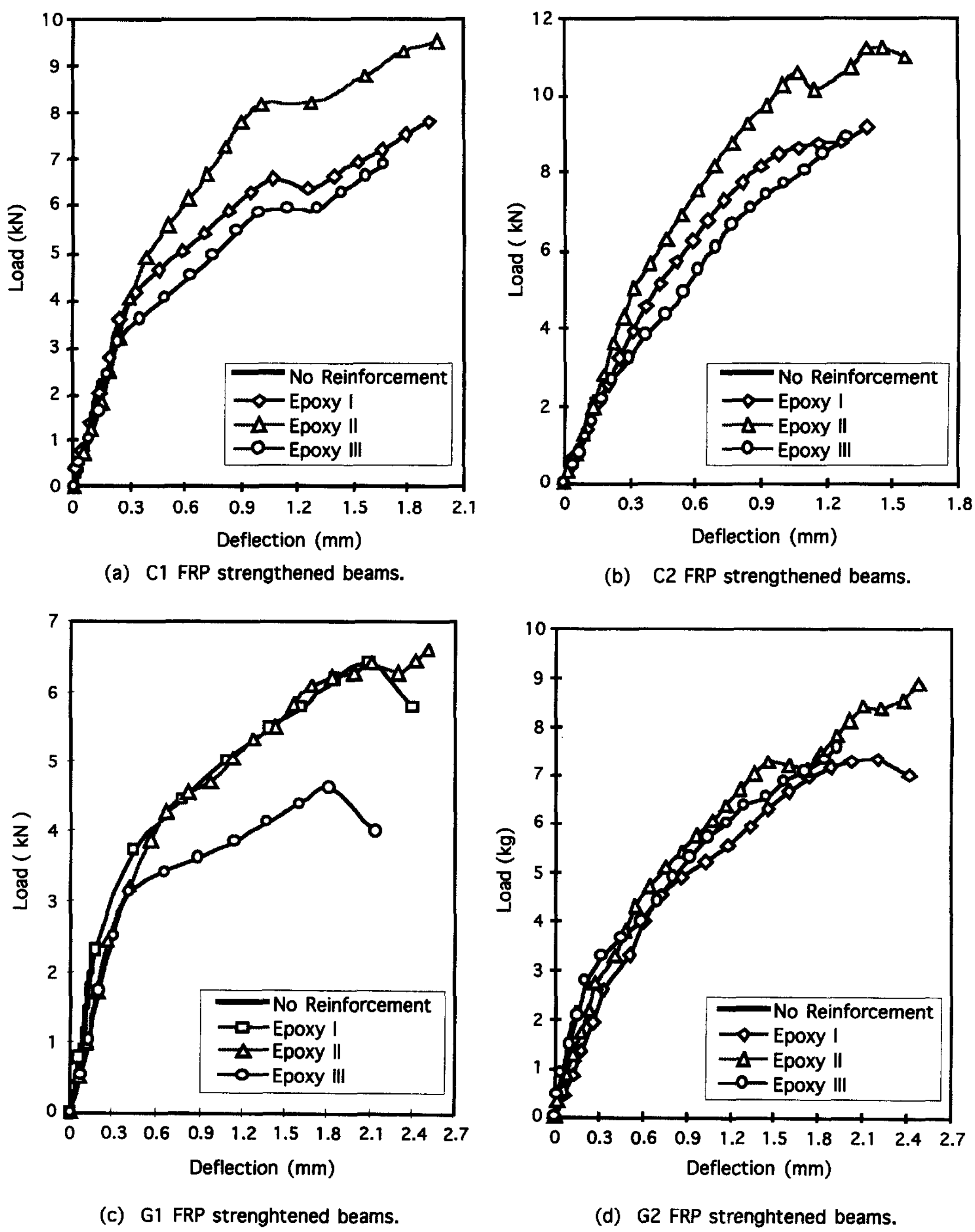
Figure 3(a–d) shows load versus deflection at midspan for all specimens using different epoxy systems. For the same type of FRP sheet strengthening, the maximum deflection exhibited by beams bonded using epoxy II was the highest compared with those bonded using epoxies I or III, and beams bonded using epoxy III exhibited the least deflection. Therefore, based on this work, strengthening by bonding an FRP sheet to the tension side of a concrete beam using epoxy II gives the beam higher flexural strength and higher ductility compared with using epoxies I or III under room temperature conditions.

Wet/dry exposure

Even with the harsh environments of wet/dry cycling, the beams exhibited a significant increase in load capacity when FRP sheets were externally bonded to the tension face. Under wet/dry environments, the ratio of the ultimate flexural load of strengthened beams to unstrengthened beams was 2.1 to 4.4, depending on the type of FRP sheets and the type of epoxy resin. However, the increase in the ultimate load decreased due to wet/dry exposure. Comparison between the ratio of the ultimate flexural load of strengthened beams to unstrengthened for wet/dry conditions and that of unconditioned (room temperature) is shown in Fig. 4.

It was difficult to draw any conclusion about whether the reduction in strength was due to the deterioration of the FRP, since the fibers did not break at specimen failure but rather debonded at the fiber–concrete interface. The reduction in strength may be attributed to the deterioration in the interface and the bond between the fiber and the concrete. The reduction in the improvement of the flexural load due to wet/dry exposure compared with room temperature is shown in Fig. 5. Beams bonded using epoxy I experienced the highest reduction in strength, between 19 and 33%; beams bonded using epoxy II experienced a reduction between 10 and 24%; and those bonded using epoxy III experienced a reduction between 3 and 8%.

There was an increase in the flexural load of unstrengthened concrete beams due to wet/dry exposure. The flexural load increased by as much as 23%, from 2.2 to 2.7 kN. The improvement in strength is attributed to accelerating



(a) C1 FRP strengthened beams.

(b) C2 FRP strengthened beams.

(c) G1 FRP strenghtened beams.

(d) G2 FRP strenghtened beams.

Fig. 3. Typical load–deflection behavior of specimens at room temperature.

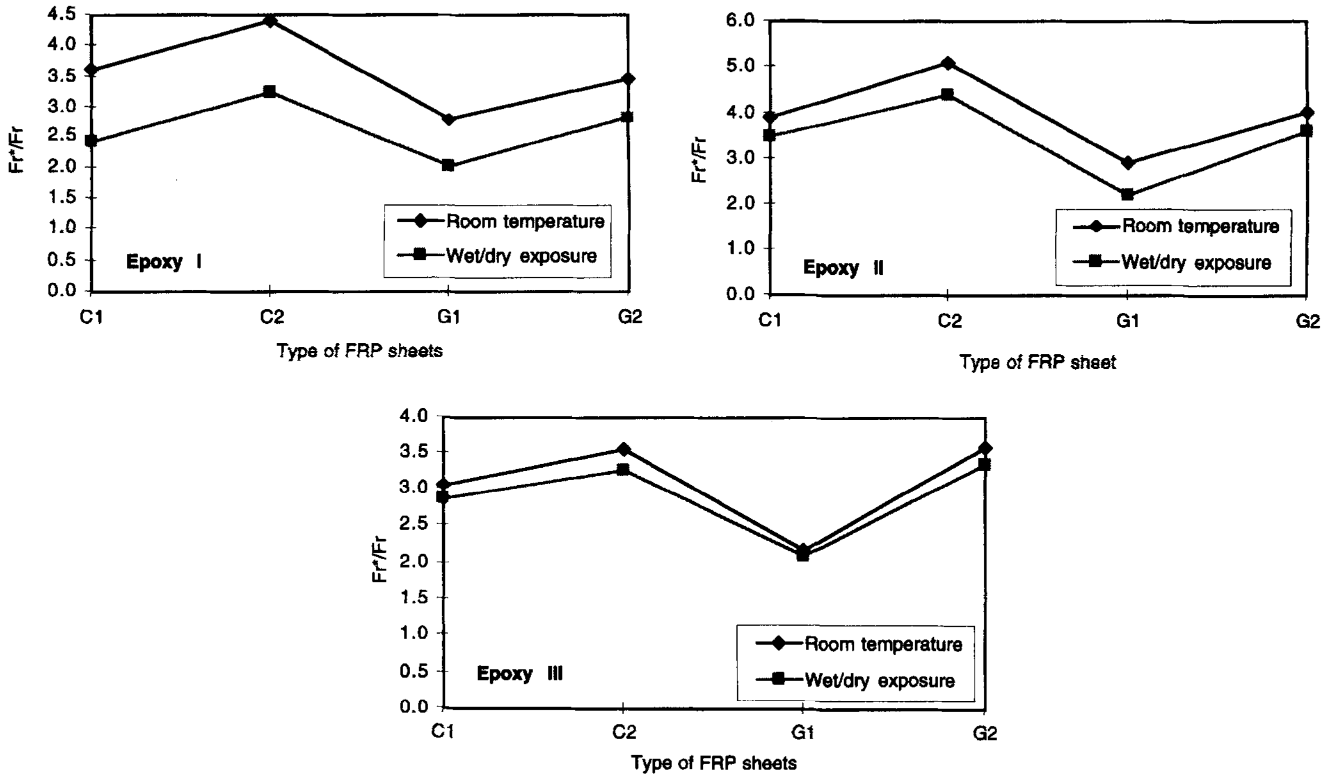


Fig. 4. The ratio of maximum flexural load of FRP-bonde beams to those of unbonded for different FRP sheets.

the aging process due to 90% humidity and high heat, which was up to 35°C.

Typical load–deflection curves at midspan for all strengthened specimens are shown in Fig. 6(a–d). Results show that beams bonded with FRP tow sheets using epoxy III exhibited maximum deflection under wet/dry environmental conditions, compared with those bonded using epoxies I or II. Beams bonded using epoxy II exhibited the most reduction in deflection but

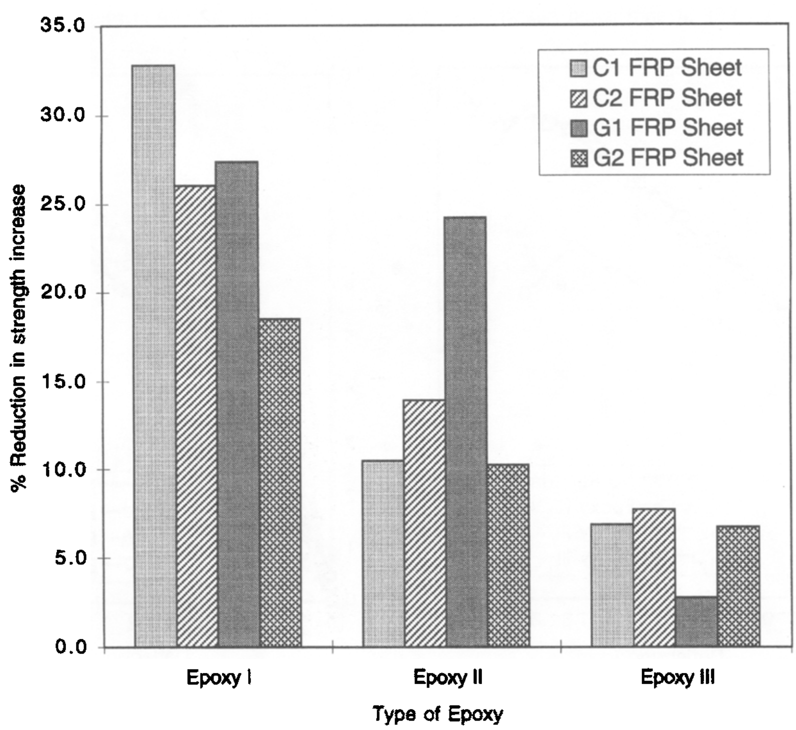


Fig. 5. Percentage reduction in strength due to wet/dry exposure.

exhibited the highest load capacity compared with the other epoxies.

CONCLUSION

Durability tests were performed to determine the potential use of FRP sheets as strengthening materials in harsh environments. The influence of wet/dry exposure on the ultimate load carrying capacity and ductility of concrete beams externally bonded with FRP tow sheets to the tension face was evaluated. Results showed that specimens subjected to wet/dry environmental conditions and those kept at room temperature exhibited significant improvement in load capacity when FRP sheets were bonded to the tension face of the concrete beams. However, the specimens subjected to wet/dry conditions showed less improvement than those kept at room temperature. The reduction in strength improvement may be attri-

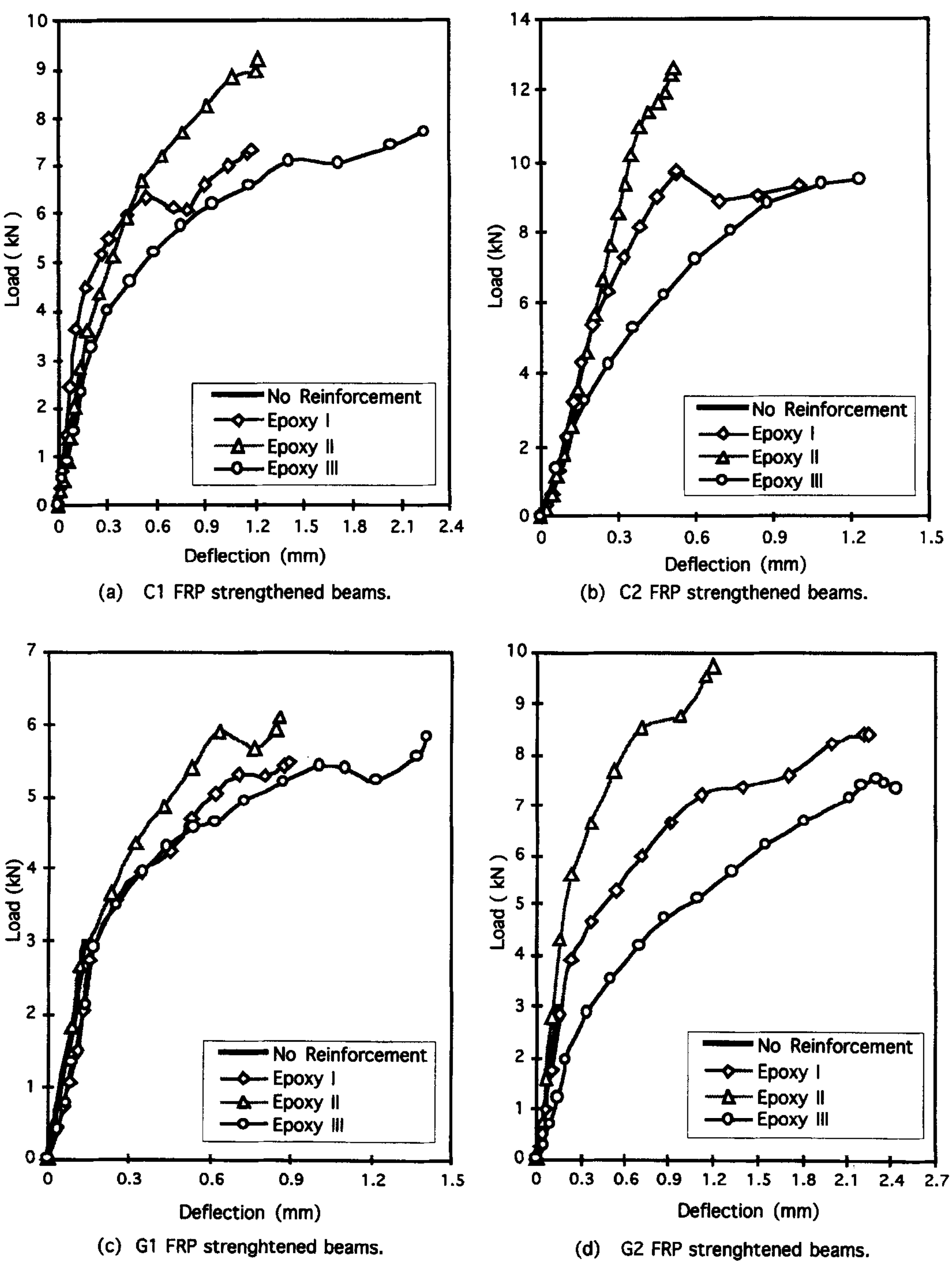


Fig. 6. Typical load–deflection behavior of specimens exposed to wet/dry conditions.

buted to the degradation of the epoxy, which led to the weakening of the bond between the concrete specimens and the FRP sheets.

Beams bonded with any of the four FRP sheets (C1, C2, G1, and G2) using epoxy II exhibited the highest load capacity, under either condition, room temperature or wet/dry, compared with those bonded using epoxies I or III. The epoxy II beams exhibited the maximum deflection at failure under room temperature exposure and the least deflection under wet/dry conditions. Therefore, when considering the FRP strengthening technique to be used in a marine environment, the selection of a suitable epoxy is very important.

The effect of environmental conditions on the FRP sheets can only be evaluated accurately if full FRP action takes place, which is the failure of the FRP sheets. This phenomenon did not occur in this study.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support of the National Science Foundation CAREER Grant CMS-9501541. The contribution of materials from Tonen, Inc. and Hexcel Fyfe, Co. are also gratefully acknowledged.

REFERENCES

1. Plevris, N. & Triantafillou, T. C., Time-dependent behavior of RC members strengthened with FRP laminates. *ASCE Struct. Eng. J.*, **120**(3), (1993) 1016–1042.
2. Triantafillou, T. C. & Plevris, N., Strengthening of R/C beams with epoxy-bonded fiber composite materials. *Mater. Struct.*, **25** (1992) 201–211.
3. Ritcher, P. A., Thomas, D. A., Lu, L. W. & Connelly, G. M., External reinforcement of concrete beams using fiber reinforced plastics. *ACI Struct. Eng. J.*, **88**(4), (1991) 490–500.
4. Saadatmanesh, H. & Ehsani, M., RC beams strengthened with GFRP plates: part I experimental study. *ASCE Struct. Eng. J.*, **117**(10), (1991) 3417–3433.
5. Saadatmanesh, H. & Ehsani, M., RC beams strengthened with GFRP plates: part II analysis and parameters study. *ASCE Struct. Eng. J.*, **117**(10), (1991) 3434–3455.
6. Hamoush, S. A. & Ahmad, S. H., Debonding of steel plate-strengthened concrete beams. *J. Struct. Eng. ASCE*, **116**(2), (1990) 356–371.
7. Rostasy, F. S., Hankers, C., & Ranisch, E. H., Strengthening RC and PC Structures with bonded FRP plates, *Proceedings of the First International Conference on Advanced Composite Materials in Bridges and Structures*, Sherbrooke, Canada, 1992, pp. 253–263.
8. Duening, M., Post-strengthening of concrete structure with pretenium advanced composites, Research Report, No. 224, EMPA D Ü Bendurf, Switzerland, 1993.
9. Kaiser, H., Strengthening of reinforced concrete with epoxy-bonded carbon-fiber plastics. Ph.D. Thesis, ETH, Zurich, Switzerland, 1989.
10. Javed, S., Kumar, S. V., & GangaRao, V. S., Experimental behavior of concrete beams with externally bonded carbon fiber tow sheets. Presented at the *51st Annual Meeting of SPI/CI Conference and Exposition*, Feb. 1996.
11. Rahman, A. H., Kingsley, & Crimi, J., Durability of a FRP grid reinforcement. *Proceedings of the Second International Conference on Advanced Composite Materials in Bridges and Structures*, Montreal, Canada, 1996, pp. 681–690.