GFRP-Bonded RC Beams under Sustained Loading and Tropical Weathering

by M.K. Saha and K.H. Tan

Synopsis: A study on glass FRP-bonded RC beams subjected to sustained loading under tropical weathering is reported. Beams were observed for long-term deflections and cracking due to sustained loading over different periods of time, after which they were unloaded and subsequently tested to failure. Beams subjected to outdoor tropical weathering for six months showed 8% larger deflections and 15% larger crack widths compared to those kept under ambient laboratory condition. Under accelerated weathering in a chamber, similar increase in deflections and crack widths were observed. Also, after six months of accelerated weathering, the ultimate flexural strength was about 17% and 12% less for beams bonded with uni- and bi-directional glass FRP laminates, respectively, compared to the un-weathered reference beams. The failure mode changed from concrete crushing to FRP rupture with weathering period, indicating the deterioration of FRP laminates. The effect of weathering was more detrimental in the presence of sustained loads.

Keywords: beams (support); cracking; deflection; fiber-reinforced polymer; flexural strength; glass fibers; long-term effects; sustained loading; weathering

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INTRODUCTION

Long-term performance is a much-recognized but less-addressed issue in the field of reinforced concrete (RC) structures strengthened with externally bonded fiber reinforced polymer (FRP) system. This type of structure may show increased deflections and crack widths over time and may also fall short of the safety margin against the ultimate collapse state when subjected to weathering effects in addition to sustained loading. Although concrete is proven to be well-resistant against both of them, concerns prevail as regards to the degradation in performance of externally bonded FRP laminates over long period of exposure to weathering. The creep effect on FRP laminates due to sustained loading would be another concern as this may accelerate the degradation due to weathering effects.

Separate studies have been reported on FRP-bonded RC beams subjected to weathering (Almusallam et al. 2001; Leung, Balendran, and Lim 2001; Liew 2003; Liew and Tan 2003) or sustained loading (Saha and Tan 2004). A study by Almusallam et al. (2001) revealed that under an exposure period of twelve months, neither did the solar radiation nor the wet-dry condition cause any significant influence on the flexural strength or rigidity of the beams (150 mm x 150 mm x 1200 mm) bonded with glass FRP laminates. A study by Leung, Balendran, and Lim (2001) on carbon FRP-bonded concrete beams (of dimensions 75 mm x 75 mm x 300 mm, without any internal reinforcement) showed improvement in the loading response when the beams were exposed to elevated temperature (during heating/cooling cycles) while water immersion for a long time (tested up to six months) gave rise to reduction in flexural capacity.

Liew and Tan (2003) studied the accelerated weathering effects of tropical climate on RC beams (100 mm x 100 mm x 700 mm) bonded with glass FRP laminates. They concluded that the glass FRP-strengthened beams showed the same failure mode when protected from weathering effects while short-term (less than one month) outdoor weathering enhances the flexural behavior. They also concluded that periods of six to nine months exposure resulted in the change in failure mode with a marginal drop of 2% in flexural capacity whereas weathering for more than six years reduced the flexural strength by 15% due to deterioration of bond between FRP and concrete.

No studies, however, have been reported on the long-term performance of structural members bonded with external FRP system that are subjected to simultaneous weathering and sustained loading effects, which is the most realistic phenomenon. This paper reports a study to address this issue. RC beams bonded with external glass FRP (GFRP) laminates were observed for long-term deflections and cracking under simultaneous effects of weathering and sustained loading for different time periods after which they were unloaded and tested to failure statically. Test results are compared with the identical set of beams subjected to weathering effects only (Liew 2003).

RESEARCH SIGNIFICANCE

This paper reports the structural performance of FRP-bonded RC beams subjected to sustained loading under tropical weathering for a maximum equivalent outdoor period of three years. The long-term deflection and crack width were found to increase while the flexural strength and ductility of the beams reduced with increasing period of weathering compared to unweathered specimens. This investigation provides information that is unique in the sense that the effect of sustained loading is combined with the impact of weathering.

EXPERIMENTAL INVESTIGATION

A total of eighteen beams were prepared, of which two beams were taken as reference beams which were neither subjected to sustained loading nor any weathering effects. Two beams each were sustained loaded and kept under ambient laboratory condition and outdoors, while the remaining twelve beams were kept in the weathering chamber that simulates outdoor weathering at an accelerated rate of six (Liew and Tan 2003). After different periods of exposure, they were unloaded and tested to failure in four-point loading.

Test program

The test program is shown in Table 1. The test parameters were type of glass FRP system, exposure condition and exposure duration. The beams were designated as Xm-t, where 'X' denotes the exposure condition (that is, 'A' for ambient, 'E' for exterior/outdoor and 'C' for chamber), 'm' is the type of glass FRP system (that is, '1' for uni-directional and '2' for bi-directional) and 't' indicates the actual duration of weathering in days (d) or months (m). For example, C1-6m refers to a beam bonded with uni-directional GFRP undergoing six months of weathering in the chamber (equivalent to three years in outdoor) before it was tested statically to failure.

Two beams (A1-0d and A2-0d) were tested without being subjected to weathering or sustained loading to serve as reference specimens. Another two beams (A1-6m and A2-6m) subjected to sustained loading were placed in ambient laboratory condition and two more (E1-6m and E2-6m) were kept in outdoor under natural weathering condition for six months. Twelve beams (from C1-5d to C2-6m) were subjected to sustained loading and accelerated weathering in the weathering chamber, and tested to failure after 5 and 15 days, and 1, 2, 3 and 6 months consecutively.

Material properties – The mix proportion for concrete was set at 1:1.96:2.6:0.53 by the weight of Ordinary Portland Cement, natural sand, crushed granite of 10 mm nominal size and water. Average cube strength and modulus of elasticity were 42 MPa and 24.8 GPa, respectively at 28 days.

Two types of reinforcement bars were used; hot-rolled deformed high yield bars (T6 – 6 mm diameter) as tensile reinforcement and hot rolled plain round mild steel bars (R6 – 6 mm diameter) as compressive reinforcement. The average yield strength and modulus of elasticity of the tensile reinforcement bars were 525 MPa and 200 GPa, respectively.

The properties of uni- and bi-directional glass fibers and resin, as supplied from the manufacturer, are shown in Table 2. Uni-directional roving and bi-directional woven roving E-glass fiber sheet were used with a two-part, 100% solid, and low viscosity amine cured epoxy to form the G1 and G2 laminates, respectively. Primer was used, according to the manufacturer's instructions, to prepare the beam surface for proper bonding of GFRP laminates.

Beam description – Normal RC beam specimens of dimensions, 100 mm x 100 mm x 700 mm, were fabricated. For the tensile reinforcement, two 6-mm diameter deformed high yield bars were used at a depth of 76 mm from the top of the beam. For the compressive reinforcement, two 6-mm diameter mild steel bars were placed at a depth of 24 mm from the top face. A ply of uni-directional (G1) GFRP laminate of 50 mm width and 0.80 mm thickness or bi-directional (G2) GFRP laminate of 100 mm width and 0.70 mm thickness were placed on the tensile face of the beams.

The width of FRP laminates was different so as to achieve similar strengthening ratio. Carbon Fiber Sheet (CFS) of 100 mm width was wrapped transversely over the beams at the FRP cut-off points to prevent premature debonding of the GFRP laminate from the beam surface.

Sustained loading

Except for the reference specimens, all beams were clamped in pairs using transverse stainless steel bars at the beam ends, as shown in Fig. 1, with steel rods placed in between the beams at one-third points, to simulate the sustained loading. The sustained load level was selected as $0.59P_1$ (or $P_1/1.7$) where P_1 is the flexural load capacity of the beam bonded with one ply of the GFRP laminate.

Weathering factors and simulation

Weathering characteristics – In this study, weathering under tropical climate was considered. Tropical climate (as in Singapore), is characterized by a hot and humid weather with very little seasonal variation in temperature or precipitation throughout the year. Table 3 shows the monthly weathering factors of Singapore (Liew and Tan 2003). The diurnal temperature range is small, with temperatures rarely below 23^0C or above 33^0C. July is the driest month of the year, while the wettest season falls between November and January. Except the above period, the monthly rainfall ranges between 100 to 180 mm. Also, on average, Singapore receives not less than four sunshine hours per day. Mean daily relative humidity is as high as 80% to 90% at night and 50% to 60% during the daytime.

Weathering chamber – A ferrocement weathering chamber (1500 mm x 1000 mm x 700 mm) was used to simulate the outside weathering effects in the laboratory (Liew and Tan 2003) (Fig. 2). The bottom and side walls were constructed with 30 mm thick, wire mesh reinforced concrete. The chamber sits on top of a water tank made of the same material. The top of the chamber was covered with a wooden lid.

To reproduce the sunlight within the chamber, a UV light source was used. Ceramic heaters were used to produce necessary heat. To control the air temperature within the chamber, thermostats were connected to the heaters. Water atomizer was used to simulate the rainfall, and this was connected to the water pump which can be controlled for a prescribed rate of water flow.

The validity of the weathering chamber in reflecting the equivalent outdoor weathering has already been established by Liew and Tan (2003). The verification was made in terms of weathering factors (that is, temperature and relative humidity) and material properties (that is, strength, ultimate strain and modulus of elasticity). Each cycle of accelerated weathering simulated the average daily outdoor weather. The weathering was therefore carried out an accelerated rate of six compared to natural outdoor weathering.

Test set-up and instrumentation

During the weathering period, the mid-span deflection of the beams was measured periodically using a demec gauge system (Fig. 1) with an accuracy of 0.002 mm and the crack width was measured using a hand-held microscope which has a graduated scale in divisions of 0.02 mm.

At the end of each designated weathering period, the specimens were tested in four-point loading using an Instron universal testing machine with a constant cross-head speed of 0.2 mm/min up to failure. Strain gauges were mounted both on the top concrete surface and on the GFRP laminate to measure the strains at each load level. Strain gauges were also installed on the internal tensile reinforcement bars at mid-span. The mid-span deflection was monitored by a Linear Variable Displacement Transducer (LVDT) placed underneath the center of the beam. Crack widths were measured in the pure moment zone at 5-kN interval using the hand-held microscope.

TEST RESULTS AND DISCUSSION

Under sustained loading

Deflections – The beams were subjected to sustained loads for a maximum period of six months. Fig. 3(a) compares the total deflections of beams subjected to outdoor weathering (E1-6m and E2-6m) with those kept in ambient laboratory condition (A1-6m and A2-6m). Beams E1-6m and E2-6m were found to deflect by about 8% more than A1-6m and A2-6m after six months. The total deflections observed on beams with G1 FRP laminates kept in chamber (i.e. C1 beams) and beams with G2 FRP laminates (C2 beams) are shown in Fig. 3(b). The solid lines present the average of the observed deflections. After six months of accelerated weathering, which is equivalent to three years under outdoor weathering, Beams C1-6m and C2-6m deflected 8% and 10% more than Beams A1-6m and A2-6m, respectively. However, Beam C1-6m was observed to show 10% less deflection than Beam C2-6m.

Crack widths – A comparison between the maximum crack widths observed in beams exposed to outdoor weathering and those kept in ambient laboratory condition is shown in Fig. 4(a). Beams E1-6m and E2-6m showed 9% and 15% wider cracks at mid-span than A1-6m and A2-6m, respectively. The crack widths observed for C1 and C2 beams are shown in Fig. 4(b). After six months of accelerated weathering, Beams C1-6m and C2-6m were found to have 36% and 39% wider cracks than Beams A1-6m and A2-6m, respectively. However, Beam C1-6m showed about 17% less crack widths than Beam C2-6m after six months.

Static load test to failure

Strength and ductility – The ultimate flexural strength of the beams bonded with G1 FRP laminates, tested after various time periods of weathering, are reported in Table 4. Beam A1-6m showed unexpectedly very low strength due to the premature debonding of GFRP at mid-span. The other beams, in general, showed a reduction in strength with longer period of weathering. After six months of accelerated weathering, the flexural strength was reduced by about 17%.

The load-deflection curves for this group of G1-bonded FRP beams are compared in Fig. 5(a). The initial stiffness of all the weathered beams was slightly less than that of the reference beam A1-0d. For short period of weathering (up to 15 days), the beams showed improved stiffness beyond the sustained load level while this improved stiffness was not visible in cases of longer periods of weathering. The improved stiffness may be due to the initial curing of concrete and FRP during short period of weathering, which vanished quickly due to deterioration of fiber-resin bond and fiber strength with longer period of weathering.

The deflections of the beams at about 59% of their respective ultimate load (correspond to service load), at steel yield load and at ultimate load are also reported in Table 4. The ductility of the beams, determined as the ratio of deflections at ultimate load and at steel yield load, was found, in general, to decrease with longer period of accelerated weathering. After six months of accelerated weathering, the ductility was found to be reduced by 38%.

The ultimate flexural strength of the beams bonded with G2 FRP laminates is reported in Table 5. These beams also showed a reduction in strength with longer weathering periods. The flexural strength reduced by about 12% after six months of accelerated weathering although Beams C2-1m and C2-2m showed unexpectedly a drop in strength of 32% and 24%, respectively. The load-deflection curves for this group of

G2 FRP-bonded beams are compared in Fig. 5(b). The curves also show the same characteristics as those for G1 FRP-bonded beams.

The ductility of the beams, as reported in Table 5, seemed to decrease with longer periods of accelerated weathering. For C2-6m, the ductility reduced by 18% compared to A2-0d.

Strains in concrete, steel reinforcements and GFRPs – The load-concrete strain, load-steel strain and load-GFRP strain curves for G1 FRP-bonded beams are shown in Fig. 6. For some of the beams that failed by concrete crushing, the ultimate strain was found to be less than 0.003. This apparent lower strain may be due to the different location of crushing point from that of the strain gauge. The lower strain in GFRP at rupture is due to the same reason.

Fig. 7 shows the strain diagrams for beams bonded with G2 FRP laminates. The behavior is similar as that for beams bonded with G1 FRP laminates.

Crack widths and failure mode – The crack widths of the beams at 59% of their respective ultimate load are given in Table 6. The crack widths of the beams decreased with longer weathering periods, which is anticipated as the ultimate strength also decreased. It is observed that the failure mode of the beams has changed from concrete crushing to FRP rupture with longer periods of weathering. This indicates that the FRP deterioration took place with increased period of weathering.

Comparison of test results with beams subjected to weathering only – The strength of the beams in this study are compared with an identical set of beams which were similarly weathered but were not subjected to sustained loads (Liew 2003) in Table 7. The beams in the current investigation were found to have 15% and 14% less strength compared to those without sustained loading for G1 and G2 FRP-bonded beams, respectively, after six months of accelerated weathering. Also, beams which were subjected to weathering in addition to sustained loading, seemed to be less ductile than those subjected to weathering only.

CONCLUSIONS

From the test investigation carried out, the following conclusions can be drawn:

1. Beams under sustained loading exhibited larger deflections and crack widths, when subjected to simultaneous weathering effects.

2. Both the strength and ductility of beams under sustained loading decreased with the longer weathering periods. The failure mode changed from concrete crushing to FRP rupture, indicating the deterioration of FRP laminates.

3. The effect of weathering is more detrimental in beams subjected to sustained loading than in those that are not.

ACKNOWLEDGMENTS

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Table 1 – Test program

Exposure condition	Exposure duration	GFRP laminates	
		Uni-directional	Bi-directional
Ambient	0 day	A1 -0d	A2-0d
	6 months	A1-6m	A2-6m
Exterior/ Outdoor	6 months	E1-6m	E2-6m
Chamber	5 days	C1-5d	C2-5d
	15 days	C1-15d	C2-15d
	1 month	C1-1m	C2-1m
	2 months	C1-2m	C2-2m
	3 months	C1-3m	C2-3m
	6 months	C1-6m	C2-6m

Table 2 – Fiber and resin properties

		G1	G2
Fiber	Type	E-Glass	E-Glass
	Sheet form	Uni-directional	Bi-directional
	Tensile strength (MPa)	1700	130
	Elastic modulus (GPa)	71	11
	Ultimate strain (%)	2.0	1.25
Resin	Type	Two part, 100% solid, low viscosity amine-cured epoxy	Same as G1
	Tensile strength (MPa)	54	
	Elastic modulus (GPa)	3	
	Ultimate strain (%)	2.5	

Table 3 – Average weathering factors (1987-1997) (Liew and Tan 2003)

Weathering factors	Monthly	
Total solar radiance energy (mWh/cm^2)	Mean	13875.90
Temperature (^0C)	Average Max. Min.	27.47 33.50 23.40
Sunshine	Max. hours/day %	8 34
Rainfall (mm)	Mean	170.40
Relative humidity (%)	Mean Max. Min.	83.11 98.70 54.10

Table 4 – Results for G1 FRP-bonded beams

Beam	Ultimate strength (kN)	Deflection at 59% load (mm)	Deflection at yield of steel, Δ_y (mm)	Deflection at failure, Δ_u (mm)	Ductility (Δ_u/ Δ_y)
A1-0d	45.18	2.70	3.23	10.58	3.27
A1-6m	32.98	2.14	2.90	5.74	1.98
E1-6m	38.44	1.49	2.11	5.12	2.43
C1-5d	42.11	2.19	3.01	10.13	3.36
C1-15d	42.98	1.71	2.53	8.83	3.49
C1-1m	36.07	1.79	2.19	6.68	3.05
C1-2m	33.07	1.50	2.13	5.51	2.59
C1-3m	32.71	1.64	2.67	6.42	2.40
C1-6m	37.42	1.75	2.56	5.16	2.02

Table 5 – Results for G2 FRP-bonded beams

Beam	Ultimate strength (kN)	Deflection at 59% load (mm)	Deflection at yield of steel, Δ_y (mm)	Deflection at failure, Δ_u (mm)	Ductility (Δ_u/ Δ_y)
A2-0d	39.36	2.22	2.89	7.18	2.49
A2-6m	37.02	2.39	2.85	6.13	2.15
E2-6m	37.57	1.19	2.00	4.21	2.11
C2-5d	36.96	1.54	2.35	6.76	2.88
C2-15d	37.30	1.54	2.47	5.64	2.28
C2-1m	26.71	1.47	4.19	7.32	1.75
C2-2m	29.92	1.53	2.42	5.74	2.37
C2-3m	34.75	2.43	2.99	7.38	2.47
C2-6m	34.79	1.52	2.25	4.59	2.04

Table 6 – Crack widths and failure mode

Duration	C1		C2	
	Crack width at 59% load (mm)	Failure mode[a]	Crack width at 59% load (mm)	Failure mode
0 day	0.28	CC	0.22	CC
5 days	0.16	CC/DB	0.20	CC/FR
15 days	0.20	CC	0.20	FR/CC
1 month	0.28	CC	0.12	CC
2 months	0.24	CC	0.26	FR
3 months	0.24	FR	0.18	FR
6 months	0.16	FR	0.16	FR

[a]CC: Concrete crushing; DB: FRP debonding; FR: FRP rupture

Table 7(a) – Effect of sustained loading in G1 FRP-bonded beams

Beam	Ultimate strength (kN)		Ductility	
	With sustained load	Without sustained Load	With sustained load	Without sustained load
A1-0d	45.18	45.38	3.27	3.30
A1-6m	32.98	46.67	1.98	3.00
E1-6m	38.44	46.52	2.43	3.60
C1-5d	42.11	46.20	3.36	3.90
C1-15d	42.98	43.70	3.49	3.10
C1-1m	36.07	47.98	3.05	2.90
C1-2m	33.07	44.73	2.59	2.40
C1-3m	32.71	n.a.	2.40	n.a.
C1-6m	37.42	44.16	2.02	2.20

n.a.- Data not available

Table 7(b) – Effect of sustained loading in G2 FRP-bonded beams

Beam	Ultimate strength (kN)		Ductility	
	With sustained load	Without sustained Load	With sustained load	Without sustained load
A2-0d	39.36	39.02	2.49	3.10
A2-6m	37.02	40.24	2.15	2.80
E2-6m	37.57	43.19	2.11	2.70
C2-5d	36.96	40.43	2.88	3.60
C2-15d	37.30	42.29	2.28	3.00
C2-1m	26.71	42.60	1.75	3.30
C2-2m	29.92	42.35	2.37	3.10
C2-3m	34.75	n.a.	2.47	n.a.
C2-6m	34.79	40.43	2.04	2.00

n.a.- Data not available

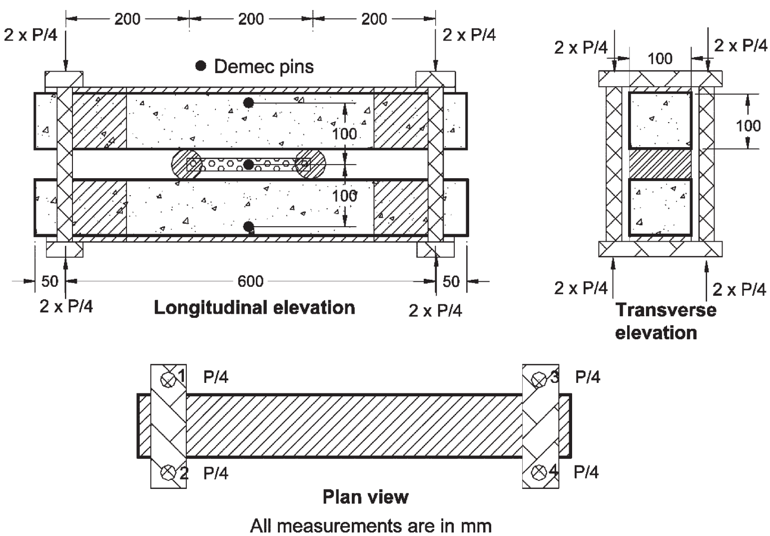

Figure 1 – Schematic drawing of beams subjected to sustained loading

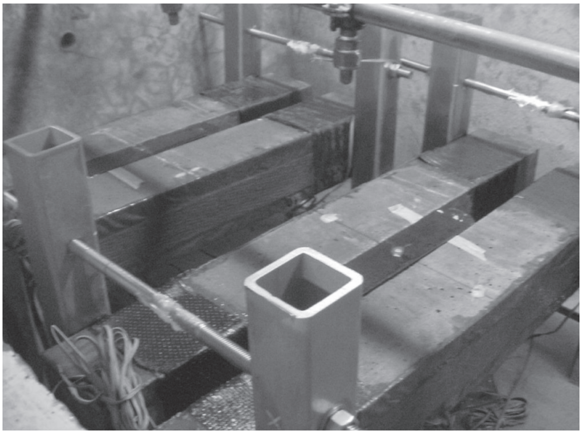

Figure 2 – Beams subjected to sustained loading inside weathering chamber

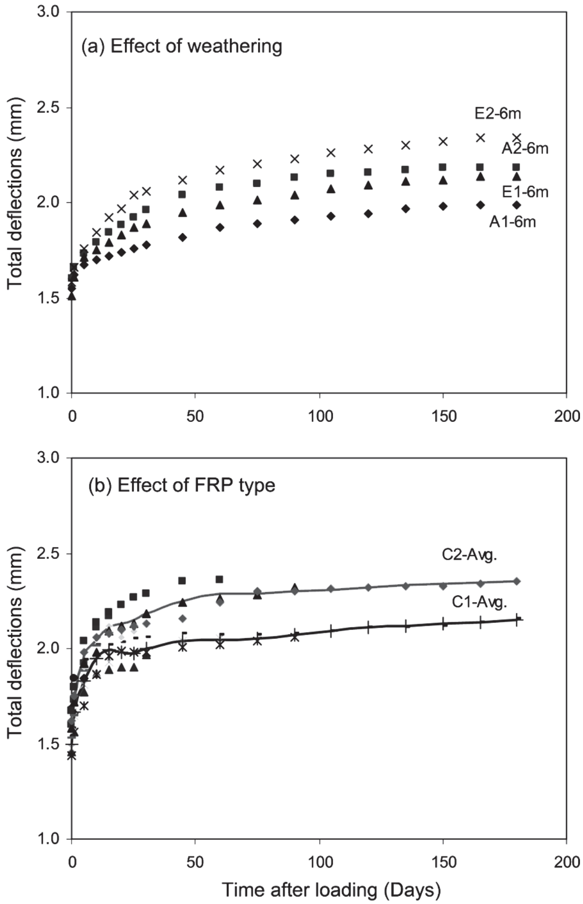

Figure 3 – Long-term deflections

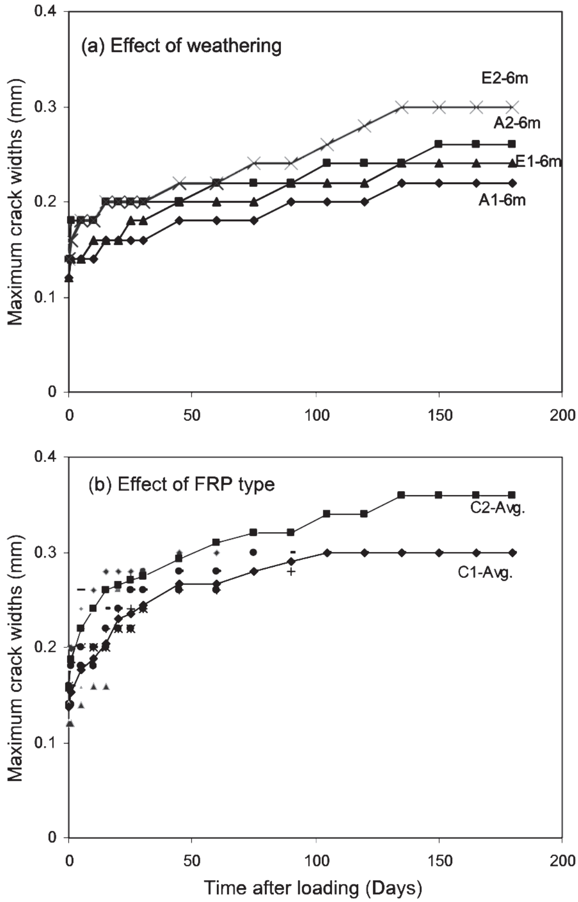

Figure 4 – Long-term crack widths

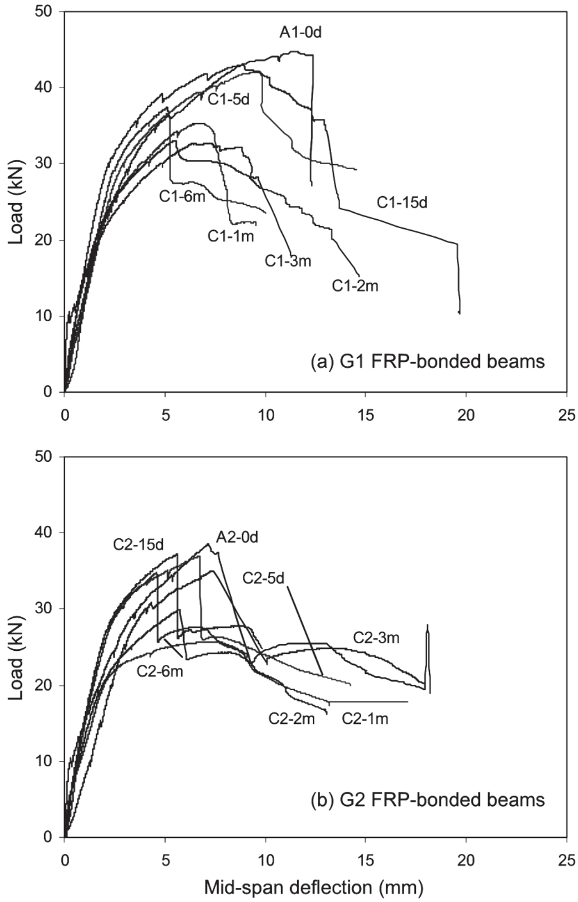

Figure 5 – Load-deflection curves

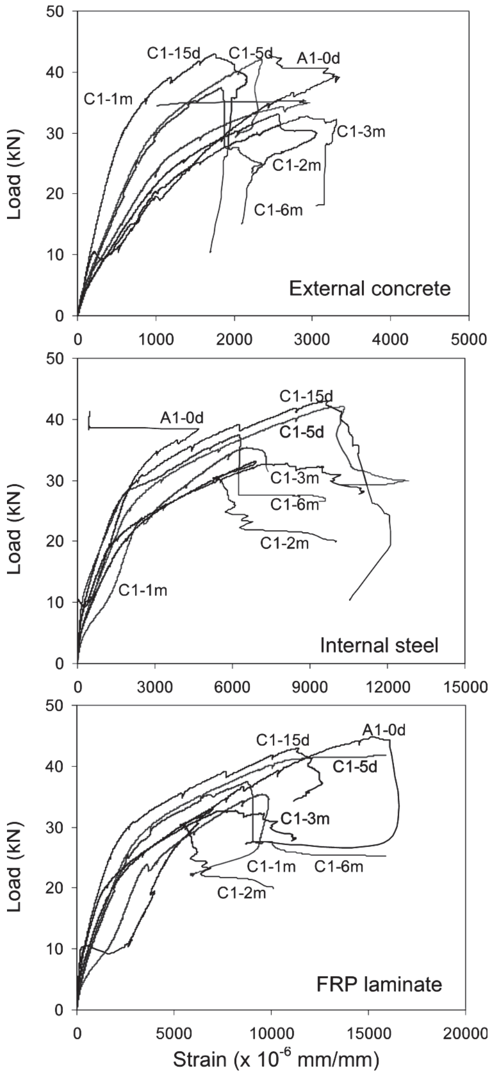

Figure 6 – Strains in G1 FRP-bonded beams

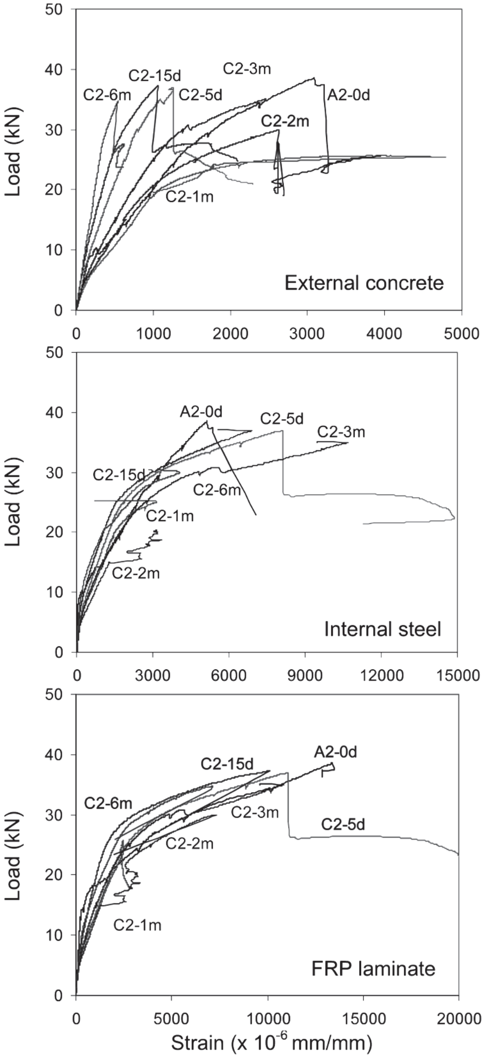

Figure 7 – Strains in G2 FRP-bonded beams