A Fracture Mechanics Approach for Interface Durability of Bonded FRP to Concrete

by J.F. Davalos, S.S. Kodkani, I. Ray, and D.M. Boyajian

Synopsis: Externally bonded GFRP fabrics are being increasingly used for seismic retrofit and rehabilitation of concrete structures, due to their high strength to weight ratio and low cost in comparison to carbon and aramid fibers. However, glass fibers are vulnerable to attack caused by harsh environmental weathering conditions such as freezing-thawing, wetting-drying, and exposure to alkaline and acidic environments. Concerned with durability, this study is based on fracture mechanics to evaluate the interface durability of GFRP bonded to Normal Concrete (NC) and High-Performance Concrete (HPC). Three types of specimens are evaluated: (1) newly bonded unconditioned specimens, (2) environmentally conditioned specimens, and (3) correspondingly base-line companion specimens. Two types of environmental ageing protocols are defined: (1) freeze-thaw cycling under in calcium chloride, used to simulate the deleterious effect of the deicing salts; and (2) alternate wetting and drying in sodium-hydroxide, used to simulate the alkalinity due to the presence of concrete pore water. Durability of the interface is characterized based on the critical strain energy release rate, under Mode-I loading, and weight and strain measurements. Considerable degradation of the interface bond is observed with increasing environmental cycling period.

Keywords: durability; external bonding; fracture toughness; FRP concrete; interface

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INTRODUCTION

Deterioration of civil infrastructure due to ageing of structures and corrosion of steel reinforcements is a major worldwide problem of pressing concern. The costs of substandard infrastructure are enormous: poorly maintained structures pose significant risk to the life of the users, and deteriorated bridges increase congestion and travel time. In 2003, the Bureau of Transportation Statistics identified about 27% of the U.S. bridges as substandard, of which about 13.7% were classified as structurally deficient and 13.8% as functionally obsolete [1]. In view of the increasing deterioration of infrastructure, in 1998 the Federal Highway Administration (FHWA) in the U.S. initiated the Innovative Bridge Research and Construction program (IBRC). The objectives of this program were: to develop new cost effective ways to use innovative materials in highway bridge applications, to develop construction techniques to reduce construction time and traffic congestion, and to develop design criteria for using innovative materials and techniques for rehabilitation of bridges [2]. The interests in rehabilitation and new construction of infrastructure have contributed to an increase in research efforts in the area of advanced materials such as polymer composites, high-performance concrete, high strength weathering steel, wood composites, and hybrid combinations of polymer composites with conventional materials.

Concrete repair using externally bonded fiber-reinforced polymer- or plastic- (FRP) laminates and wet lay-up fabrics constitutes a leading application of composites in the

IBRC program [3]. Surface bonded glass-fiber (GFRP) or carbon-fiber (CFRP) plates and fabrics have been successfully used to retrofit masonry, wood and concrete structures damaged or weakened by impact, earthquake or ageing. Such repairs can be carried out more rapidly in comparison to other traditional techniques and hence reduce the construction and traffic closure time. However, due to a short history of these materials in the field of infrastructure there is a need to establish long-term durability of this rehabilitation technique, when subjected to environmental weathering. Hence this study evaluated the interface durability of E-glass fiber-reinforced polymer (GFRP) bonded to normal and high-performance concretes subjected to 400 freeze-thaw cycles in calcium chloride and 30 wet-dry cycles in sodium hydroxide solutions. The performance of the interface is characterized based on the critical strain energy release rate, weight and strain measurements. The deterioration of the environmentally conditioned specimens is gauged relative to the unconditioned companion specimens. Considerable interface degradation and decrease of fracture toughness is observed after environmental conditioning of the specimens.

SINGLE CONTOURED CANTILEVER BEAM (SCCB) SPECIMEN TEST METHOD

Several studies have characterized the behavior and durability of FRP-concrete bonded interface based on ultimate load and displacement values obtained either from bending or pull-out tests. Considering that delamination or peeling is the most prevalent mode of failure in FRP retrofitted structures, it would be more appropriate to characterize the interface durability based on parameters that are more representative of the interface strength, such as strain energy release rate, G, which is generally obtained using the standard double cantilever beam specimen (DCB) or contoured double cantilever beam (CDCB) specimen under Mode-I, or opening mode, loading. The fracture energy has been extensively used to study the durability of bonded metal, wood and composite interfaces. However, owing to the low tensile strength of concrete, the application of opening-type test specimens to evaluate the FRP-concrete interface results in the fracture of concrete rather than an interface failure. To overcome this difficulty, in the present study we use the Single Contoured-Cantilever Beam (SCCB) specimen (see Figures 1 and 2), to evaluate the GFRP-concrete interface.

The SCCB method makes use of a tapered wood contour as a means of achieving constant compliance *(C)* rate change with respect to crack length *(a)*, or dC/da. The design of the test specimen is based on previous work for the contoured double cantilever beam (CDCB) for bonded interfaces by Davalos et al. [4, 5, and 6]. The analytical solution was modified later by Qiao et al. [7] to incorporate the crack-tip deformation in the computation of the total compliance of the CDCB specimen. Using this test method, one avoids the measurement of crack length, which is generally difficult to obtain. However, the SCCB specimen needs to be calibrated carefully to achieve a confident range of constant dC/da to directly obtain critical strain energy release rate G_c.

MATERIALS

The SCCB specimen was fabricated at the concrete laboratory of West Virginia University using six different materials, including the two substrates: normal or high-performance concrete, E-glass fiber reinforced polymer (GFRP), primer, saturant, and yellow poplar laminated veneer lumber (LVL). The properties of the materials used are discussed in detail by Davalos et al. [8].

EXPERIMENTAL PROGRAM

The experimental program consists of the following steps:

Design, analysis, and calibration of the Single Contoured-Cantilever Beam specimen, which is used to evaluate interface fracture of the GFRP-concrete materials;

Casting and conditioning of the concrete specimens, and procedures for bonding both the GFRP to concrete and the wood contour to the GFRP;

Testing and evaluation of interface fracture of the SCCB specimens under Mode-I loading, including dry, and freeze-thaw and wet-dry cycling conditions.

A flowchart summary of the experimental plan is given in Figure 4.

COMPLIANCE CALIBRATION

Mode-I fracture of materials are commonly evaluated using the Double Cantilever Beam (CDCB) specimen, with the energy release rate, G, being computed from:

$$G_c = \frac{P_c^2}{2b}\frac{dC}{da} \tag{1}$$

where, the critical value G_c corresponds to the critical load P_c; b = width of specimen, and dC/da = rate of compliance(C) with respect to crack length (a). For a constant cross-section DCB specimen, dC/da is an exponential function, typically obtained experimentally, and in such case, the crack length needs to be measured as the crack front propagates; such a measurement is a difficult task.

To avoid the measurement of crack length, a, the contoured (CDCB) or Tapered (TDCB) specimen is used, for which dC/da is constant. This concept was applied by Davalos and co-workers (Davalos et al. [4, 5, and 6], and Qiao et al. [7]) for wood-wood and wood-FRP bonded interfaces, by their development of a CDCB specimen for hybrid material interfaces. Their approach consists of defining analytically the shape of the specimen contour, which is then approximated by a linear function to define a tapered section with a constant slope. This approximate specimen is then calibrated experimentally to obtain, as precisely as possible, the actual dC/da value. Compliance calibration of the fracture test-specimen is important in this study, because the accuracy with which the strain energy release rate is computed depends on the precision with which the compliance rate-change (*dC/da*) is defined as a constant value.

The compliance evaluation was performed in three stages: (1) a finite element model of the symmetric *CDCB wood* specimen (CDCB), exploiting symmetry and using ABAQUS 6.1 with 4-node plane stress elements; (2) an experimental calibration of the symmetric CDCB wood specimen, using a servo hydraulic operated MTS machine, and an MTS clip-on gauge connected to an external data acquisition system to collect crack-tip opening displacement (COD) for several crack lengths; (3) finally, an experimental calibration of the SCCB specimen (the actual GFRP-reinforced concrete substrate bonded atop with a wood contour, as used in this research - see Figure 3), for specimens fabricated with crack-lengths of about 102, 152, 203, 254 and 304 mm, respectively, to obtain compliance values. The results are shown graphically in Figure 5, indicating close correlations between the compliances for the symmetric CDCB specimen (from both FE analysis and testing) and the asymmetric single-contour (SCCB) actual test-specimen; this is significant because these favorable results validate using the proposed specimen for Mode-I testing. The mean *dC/da* value obtained from the SCCB calibration for a crack-length of up to about 300 mm (Fig. 5) was 2.364 x 10-5 N-1 and was used for the computation of the G_c values reported in this study.

DRY FRACTURE RESULTS

The objective of the dry fracture tests is to obtain based-line values of the critical strain energy release rate (G_c), also termed *fracture energy* of the interface bond for newly fabricated GFRP-concrete assemblies, using both normal and high-performance concretes that were not subjected to any deleterious environmental exposures. Fracture tests were performed on the SCCB specimens under displacement control at the rate of 0.0254 mm/s using an MTS machine. The SCCB specimen was tested by encasing the substrate in the testing fixture (see Figure 1) designed for this purpose. Load and crack-tip opening displacements were recorded at every one-fifth of a second by a data acquisition system as the interfaces were tested to failure. The critical strain energy release rate or the interface fracture toughness (G_c) was computed from Eq. (1).

A total of eight NC and eight HPC specimens were tested for dry fracture. The results obtained clearly exhibited differences in the fracture modes due to differences in the substrate types. As seen in Figure 6, the fracture of GFRP-HPC specimens exhibited primarily adhesive failure and propagation of the crack-front through the interface, while the GFRP-NC failure was primarily cohesive and the cracks propagated through the substrate. The critical load P_c used to obtain G_c was computed as the statistical mean of the crack initiation loads. Dry fracture tests were also performed on a total of six CFRP-concrete specimens to further evaluate the validity of the modified SCCB test method, in relation to an extensive previous study with the original design of the SCCB concept; the G_c values obtained for carbon fabric were in good agreement with the results obtained in the previous research [9], and hence confirmed the general applicability of the SCCB method. The results obtained for the dry fracture tests are presented in Table 1 and the values in the bracket indicate the standard deviation.

FREEZE-THAW PROTOCOL AND FRACTURE TEST RESULTS

Concrete structures in North America and other countries exposed to wintry weather are subjected to the deleterious effects of freeze-thaw, and for highways and bridges the deterioration process is accelerated by the application of deicing salts. Hence to simulate this effect in this study, the ASTM C-666 and C-672 [10, and 11] standards were modified appropriately to design the freeze-thaw (FT) cycling protocol to include the effect of deicing salts. The specimens were subjected to accelerated FT cycling in calcium chloride which is a representative deicing salt. The concrete specimens with surface-bonded GFRP layer on top were placed upside-down inside stainless steel trays, containing 4 % calcium chloride ($CaCl_2$) solution filled up to the level just above the interface (Figure 7a). The trays were then placed into an environmental chamber for FT conditioning, as shown in Figure 7b. A typical freeze-thaw cycle consisted of varying linearly the temperature from 20 ^{0}C to -20 ^{0}C in two hours; maintaining the temperature at -20 ^{0}C for two hours and ramping back to 20 ^{0}C in another two hours.

A total of 40 bonded (20 for each substrate type) specimens were subjected to FT conditioning in an environmental chamber (see Figure 7), and correspondingly, 16 bonded (8 for each substrate type) companion specimens were placed in an environmental room maintained at 28 ^{0}C and 50% RH. The specimens for FT conditioning were subjected to a total of 400 FT cycles, and changes in strains and weights were monitored at the end of every 100 cycles. Critical strain energy release rate was measured at the end of every 100 cycles by destructively testing the conditioned specimens in Mode-I fracture. The strains and weights were measured on all specimens initially and during the freeze-thaw cycling process at the end of every 50 cycles, with readings taken at the end of the thawing period when the temperature had stabilized to 20 ^{0}C. The strains were recorded using a Demec extensometer over a gauge length of 100 mm, and the weights were measured using an electronic balance. The specimens exhibited a rapid initial increase in strain, which later decreased as specimens approached saturation after prolonged conditioning (see Figure 8).

Critical strain energy release rate was measured at the end of every 100 cycles by destructively testing the conditioned specimens in Mode-I fracture. The reduction in the strain energy release rate of the weathered specimens was computed relative to the companion specimens of the same age. The results obtained (see Figure 9) indicate a reduction in the G_c value of the weathered specimens with increasing number of freeze-thaw cycles. The fracture surface of the GFRP-concrete interface also showed a marked reduction in the cement paste attached to the GFRP overlay, and the failure became less cohesive with increasing freeze-thaw cycling duration (see Figure 10). At the end of 100 cycles the fracture energy reduced by 38.5% for GFRP-NC and 33.5 % for GFRP-HPC interfaces (see Figure 9). This reduction in fracture energy continued to increase to 50.5% for GFRP-NC and 43.79% for GFRP-HPC specimens at 200 FT cycles. Finally, at the end of 300 FT cycles the G_c reduced by 59% for GFRP-NC and 71% for GFRP-HPC interfaces. The specimens tested at the end of 400 cycles had suffered extensive delamination at the interface, because of which the testing of these specimens did not yield any meaningful results.

WET-DRY PROTOCOL AND FRACTURE TEST RESULTS

The GFRP reinforcement used was E-glass fibers, which are composed of aluminates and boric acid components that increase their susceptibility to alkali attack. When used in civil infrastructure, the presence of groundwater, soils and concrete pore-water all contribute to creating a condition of alkalinity. Thus, in this study we evaluated the durability of GFRP-concrete interfaces subjected to wetting and drying in a sodium hydroxide solution, simulating an alkaline condition.

The wetting and drying weathering protocol defined in this study consisted of a total of 30 cycles. Each cycle included 3 days of wetting in a sodium hydroxide solution (pH=12) at room temperature and 4 days of drying in an environmental chamber maintained at 40 ^{0}C and 50% RH. At the end of every 10 cycles the specimens were monitored for strain and weight changes, and groups of specimens were tested in Mode-I fracture to obtain their critical strain energy release rates.

A total of 30 bonded specimens (15 for each substrate type) were subjected to the wet and dry (WD) weathering protocol. In addition, a total of 12 bonded companion specimens (6 for each substrate type) were placed in an environmental room maintained at 28^{0} and 50% RH; these specimens were fractured alongside their aged counterparts and the results obtained were used to gauge the performance of the aged specimens. The WD conditioned specimens exhibited much higher strain values in comparison to the companion specimens, indicating, as expected, greater differential movement between the concrete and GFRP in the aged specimens. As shown in Figure 11, the GFRP-NC interface exhibited a maximum absolute differential movement of 156 μs, and the maximum for the GFRP-HPC interface was 112 μs. These results indicate a slightly better strain compatibility of the GFRP-HPC interface. A reduction in G_c was observed with increasing number of WD cycles (Figure 12), and the failure became more brittle and sudden in comparison to the companion specimens of the same age. At the end of 10 cycles the fracture energy reduced by 31.6% for GFRP-NC and 40.0% for GFRP-HPC interfaces (see Figure 12). This reduction in fracture energy continued to increase to 50.0% for GFRP-NC and 58.0% for GFRP-HPC specimens at 20 WD cycles. Finally, at the end of 30 WD cycles G_c reduced by 72.0% for GFRP-NC and 67.9% for GFRP-HPC interfaces.

CONCLUSIONS

- For all dry fracture tests, the interface bond with NC had higher values of fracture toughness and exhibited primarily cohesive failure, with propagation of cracks along the bond line but mainly through the substrate. The GFRP-HPC interface had lower fracture toughness showing adhesive failure, and propagation of cracks primarily at the interface.

- The specimens exposed to freeze-thaw cycling had higher strain values than the companion specimens, indicating greater dimensional change in conditioned specimens. The differential movement between GFRP and concrete in GFRP-NC was found to be higher than in GFRP-HPC interface, indicating better strain compatibility of GFRP-HPC interface.

- For the FT companion specimens, G_c increased with time, and at the end of 75 days (300 FT cycles) G_c increased by 9.4% for GFRP-NC and 6.6% for GFRP-HPC with respect to the dry fracture specimens tested at time zero. This increase in G_c could be attributed to two factors: (1) the continued hydration and curing of concrete resulting in an increase in strength of the substrate, and (2) the gain in strength of polymers over extended curing periods.

- At the end of 100, 200 and 300 FT cycles the corresponding reductions in fracture energy for NC and HPC, respectively (with reference to the unconditioned companion specimens) were: 38.5% and 33.5%; 50.5% and 42.8%; and 59% and 71%.

- Owing to the extensive deteriorations caused by FT cycling, the fracture tests conducted on specimens at the end of 400 FT cycles did not yield any meaningful results.

- For the wet-dry (WD) cycling, the companion specimens also showed increases in G_c with increased times. At the end of 210 days (30 cycles) an increase of about 25% (relative to the dry fracture test results) was recorded for both NC and HPC concrete specimens. However the fracture surfaces were nearly identical to those exhibited by the dry fracture test specimens.

- The G_c for the WD conditioned specimens reduced with increased aging. At the end of 10 cycles (70 days) a reduction of 31.6% for GFRP-NC and 40.0% for GFRP-HPC was recorded. This reduction continued further to 50% for GFRP-NC and 58% for GFRP-HPC after 20 cycles (140 days). Finally, at the end of 30 cycles, G_c reduced by 72% for GFRP-NC and 68% for GFRP-HPC specimens.

The failure for GFRP-NC specimens became less cohesive with increased aging, while the failure for GFRP-HPC was primarily adhesive with propagation of the cracks through the interface. In case of GFRP-HPC a white precipitate was observed at the interface. Initially after 10 WD cycles, this precipitate was observed in the region close to the initial crack-front, and with increased ageing it was observed to propagate along the length of the specimen.

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Table 1 - Dry fracture test results

Specimen	Compressive Strength of Concrete (MPa)	Critical load (P_c) (N)	G_c (J/m^2) (Initiation)
GFRP-NC	40.6 (1.025)	1256 (62)	427 (42)
GFRP-HPC	68.25 (1.72)	1055.4 (37)	301 (21)
CFRP-NC	40.6 (1.03)	1485 (64)	597 (36)
CFRP-Concrete (previous study [8])	51.6 (2.1)	1750 (39.5)	618 (17.0)

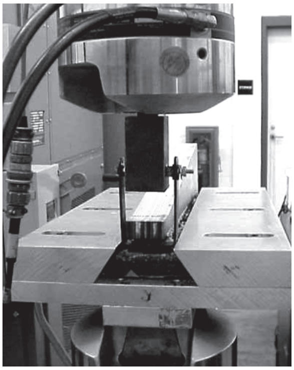


Fig. 1 - Single Contour Cantilever Beam Specimen and Fixture

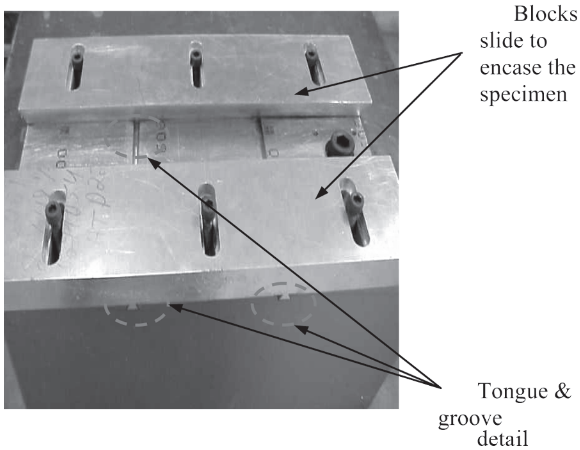


Fig. 2 - Single Contour Cantilever Beam Specimen Fixture

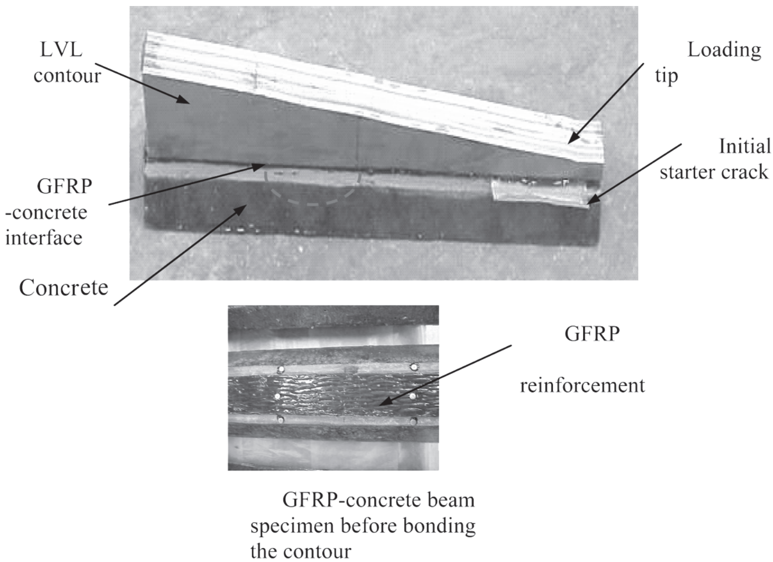


Fig. 3 - Single Contour Cantilever Beam Specimen

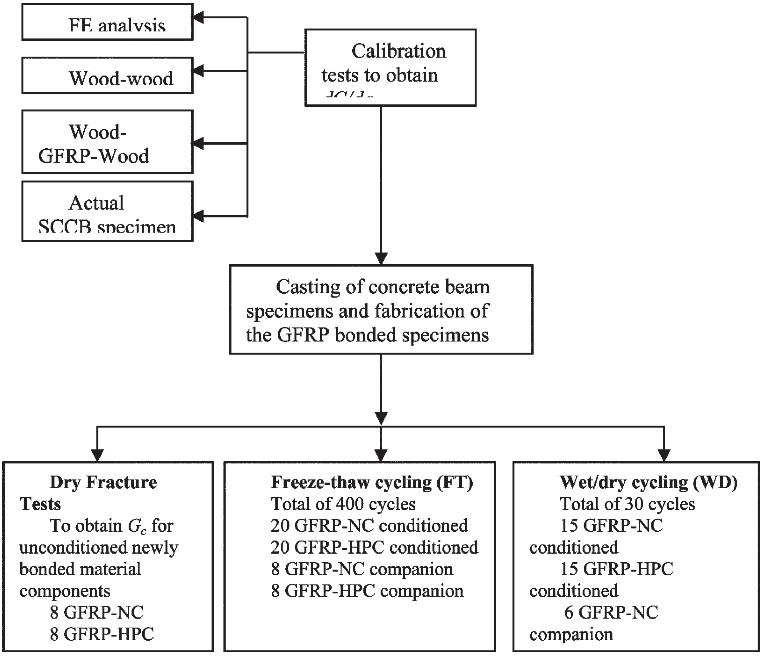


Fig. 4 - Flowchart of the experimental study program

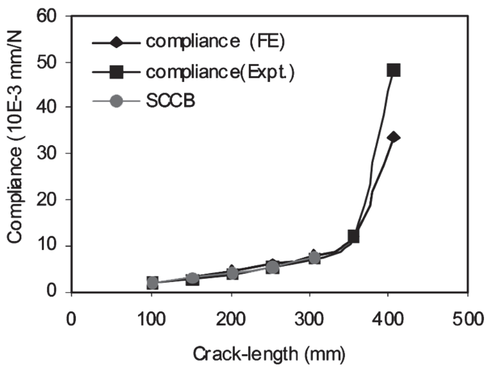


Fig. 5 - Compliance calibration results

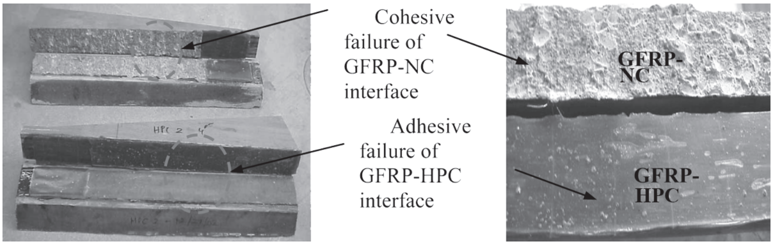
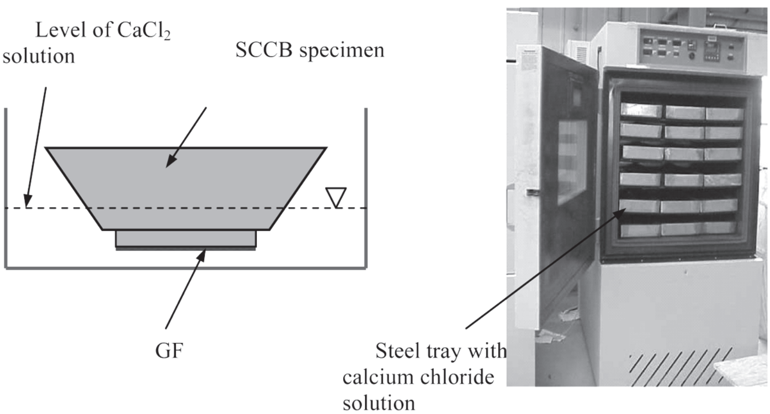


Fig. 6 - Typical fracture surfaces of GFRP-NC and GFRP-HPC specimens after dry fracture test



(a) (b)

Fig. 7 - FT cycling of specimen within: (a) a tray, and (b) an environmental chamber

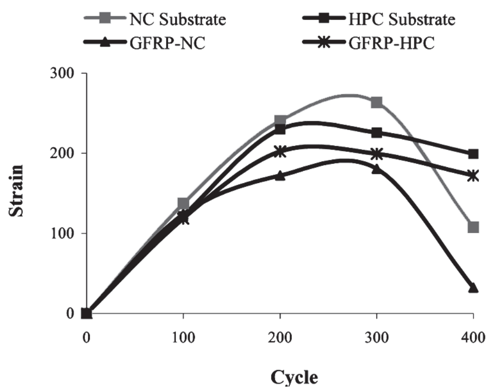


Fig. 8 - Strains in GFRP-NC & GFRP-HPC interfaces

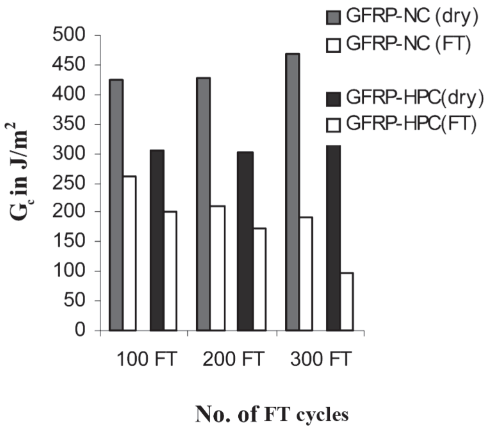


Fig. 9 - G_c values after FT conditioning

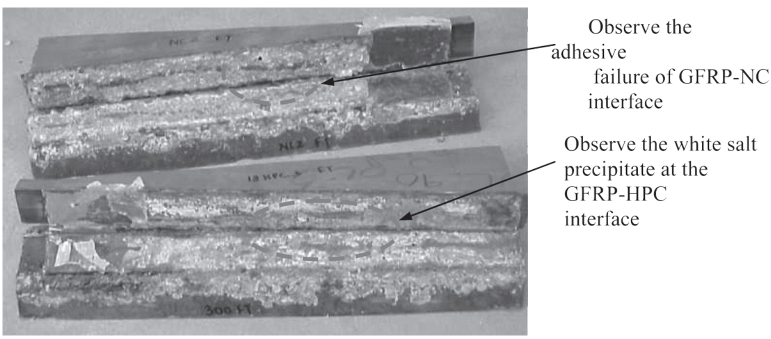


Fig. 10 Fracture surface after 300 FT cycles

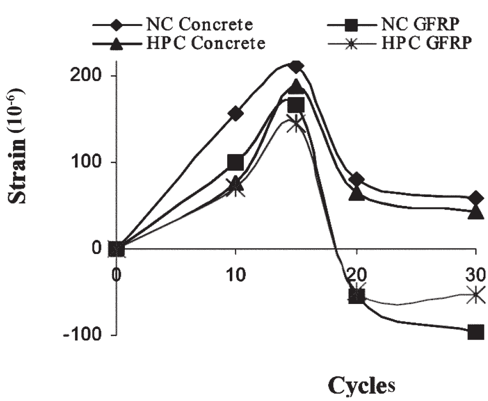


Fig. 11 - Strain behavior of WD conditioned specimens

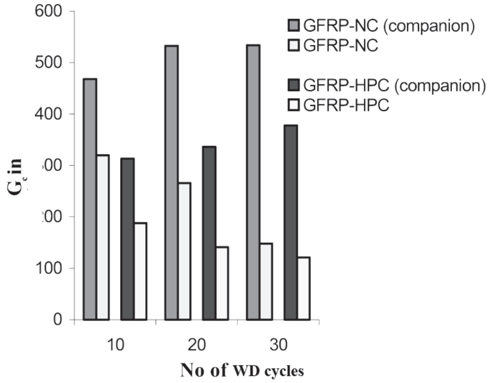


Fig. 12 - G_c values after WD conditioning

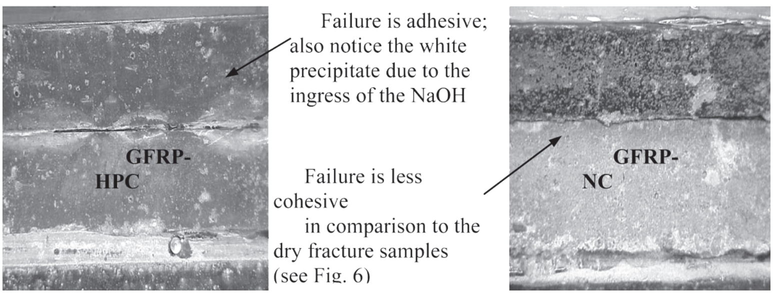


Fig. 13 - Typical Fracture Surfaces after 10 Wet-Dry Cycles