DURABILITY OF FIBRE REINFORCED POLYMERS (FRP) EXPOSED TO HIGH TEMPERATURES AND GAMMA RADIATION

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ABSTRACT

Effectiveness of fibre reinforced polymers (FRP) in repair and upgrade of concrete structures has been demonstrated repeatedly in short-term laboratory tests and field applications. FRPs have superior strength- and stiffness-to-weight ratios and are easy to use but the interest in FRP is mainly driven by the fact that they can prevent the corrosion related problems that are associated with reinforcing steel. One of the newer areas of interest in application of FRP is its potential for repairing and strengthening of nuclear containment structures and oil refineries. However, the data on the durability of FRP subjected to various environmental exposures in such structures is still lacking. The lack of durability information has been one of the main drawbacks in the industry-wide use of FRP by engineers and designers.

This paper evaluates the durability of room-temperature-cured FRP and FRP-FRP bond subjected to simulated nuclear power plant environment. The exposure environment included gamma radiation, loss of coolant accident (LOCA) scenario, and sustained and cyclic high temperatures. The behaviour of FRP-FRP bonds under stress and subjected to increasing temperature was also studied.

It was observed that FRP and FRP-FRP bonds have good resistance to almost all of the exposures studied. However, FRP-FRP bonds were unable to maintain their load carrying capacity when they were subjected simultaneously to stress (30% of ultimate) and temperatures approaching the glass transition temperature of epoxy.

1 INTRODUCTION

Although room-temperature-cured FRP used in new and existing concrete structures has demonstrated excellent structural performance, there is still a lack of understanding of their long-term durability. There is interest in exploring the suitability of FRP in specialized concrete structures such as nuclear power generation plants and oil refineries due to its resistance to corrosion and its electromagnetic properties. In these special applications FRP will be exposed to sustained high temperatures, sudden temperature spikes, gamma radiation, and a variety of chemicals. The amount of information available in the public domain on the durability of FRP subjected to the environments of these specialized structures is limited to non-existent.

This paper evaluates the durability of FRP and FRP-FRP bond subjected to a nuclear power plant environment which included gamma radiation, loss of coolant accident (LOCA) scenario, sustained high temperature, cyclic high temperature, and combination of sustained load and increasing temperature. The specimens included CFRP and GFRP coupons and CFRP and GFRP single lap bonded (SLB) specimens, which if survived the exposures were tested under static loads for their post-exposure mechanical performance.

2 EXPERIMENTAL PROGRAM

2.1 Materials and Specimens

Carbon fabric, glass fabric, and epoxy were the components of the FRP laminates. The materials are from the TYFO™ S Fiberwrap™ System. The properties of the hand wet lay-up composites as provided by the supplier are shown in Table 1. The fabric used comes in the form of woven rovings. The main glass and carbon rovings, which carry the applied loads, are aligned in the longitudinal direction and held together by non-structural Kevlar wefts. The epoxy system is a two-part resin and is mixed together in a ratio of 100:42.

Table 1: Properties of GFRP and CFRP

Property	CFRP	GFRP
Ultimate Tensile Strength (N/mm/layer)	867	575
Rupture Strain (mm/mm)	0.0121	0.022
Nominal Thickness of the Fabric (mm)	1.0	1.3
Weight of the Fabric (grams/m^2)	658	923
Weight of FRP Sheet (grams/m^2/layer)	1660	2500
Coefficient of Thermal Expansion (^{o}C)	-0.5×10^{-6}	7.7×10^{-6}

The 25 x 175 mm FRP tensile coupons (Fig. 1) were made in accordance to ASTM D 3039. The 25 x 300 mm SLB specimens (Fig. 2) were prepared in accordance with ASTM D 3163. Specimen preparation is explained in detail elsewhere[1]. Results from a total of 394 specimens are summarized here.

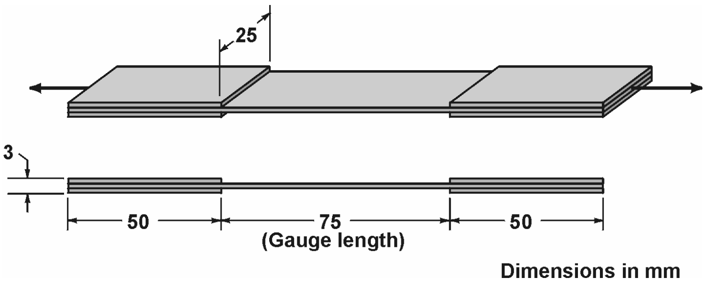

Figure 1: FRP tensile coupons

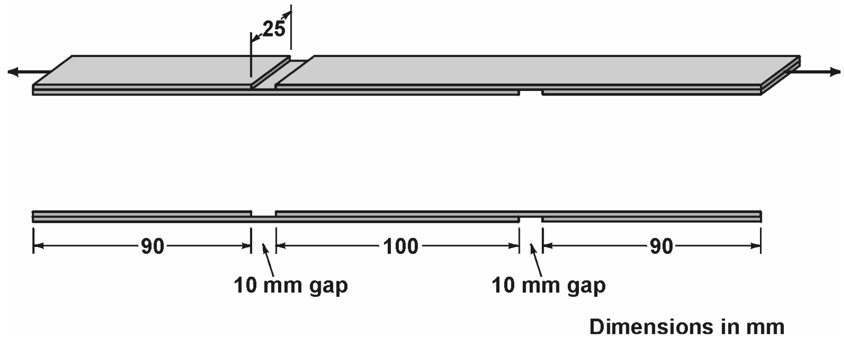

Figure 2: FRP single-lap-bonded specimen

2.2 Exposure Detail

2.2.1 Gamma Radiation

There are no reported cases of FRP being used as reinforcement in nuclear structures; hence, there are no published codes or test standards for it. However, there are standards such as ASTM D4082 and CSA N287.1 that cover the durability of organic materials, mainly coatings and sealants, used in nuclear power plants.

Ontario Power Generation (OPG)[2] specified that for materials to be used in the containment structure of nuclear power generation plants, they have to be tested for their durability to a minimum dosage of 200 kGy of nuclear radiation. This value represented a "safety factor" of four based on the information for Reactor Building 1 at Pickering NGS, which reportedly has a maximum lifetime dosage of approximately 50 kGy , including a postulated accident. The specimens in this study were exposed to 290 kGy of gamma radiation at 38°C.

2.2.2 Loss of Coolant Accident (LOCA)

The greatest risk in operating a reactor is considered to be the loss-of-coolant accident (LOCA). Such an accident would in a very short time result in evaporation of all the water in the reactor tank.

American National Standards Institute (ANSI) N101.2[3] requires LOCA test as a minimum acceptance criteria for coating materials. Since most of the research conducted on nuclear reactors is proprietary and confidential, no scientific reports on the performance of FRP subjected to LOCA scenario was found in the literature.

The specimens tested in this study were exposed to one of the LOCA scenarios used by OPG. In this scenario the specimens were subjected to a thermal spike from 40°C to 135°C over a short time (1 second, intended) and brought back to 50°C over a period of about 90 days (Fig. 3).

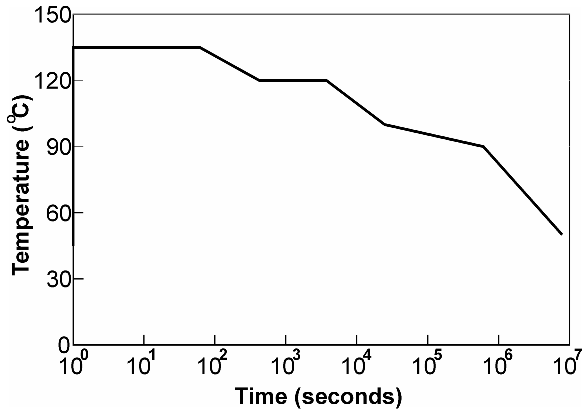

Figure 3: The LOCA scenario

2.2.3 Sustained High Temperature and High Temperature Cycling

The fibres used in FRP are manufactured at temperatures well in excess of 1200°C and are therefore immune to the operation temperatures expected in a nuclear power plant. The matrix, on the other hand, is not very resistant to high temperatures. Its performance depends on its glass transition temperature, T_g. The epoxies used in FRP for external reinforcements of concrete structures are usually cured at moderate temperatures, which possess physical properties that are very different from the ones used in aerospace or automotive industries. Therefore, the mechanical properties of room-temperature-cured FRP and their resistance to high temperature cannot be predicted based on the knowledge gained from studies on the performance of the FRP that is used in aerospace or automotive industries. The glass transition temperature of the epoxy used in this research is about 80°C.

Four sets of GFRP and four sets of CFRP specimens were tested. One set of each material was exposed to sustained high temperatures (50°C or 65°C, for three months) or to high temperature cycling (between 10°C and 50°C in air or water, four cycles a day for three months) and were tested for their post-exposure mechanical performance.

2.2.4 Increasing Temperature under Sustained Load

In this test the specimens were subjected to stresses equal to 30% of their ultimate strength in a thermal enclosure where the temperature was raised until the specimens' failure.

2.3 Mechanical Tests

After the exposures, the specimens were tested at room temperature for their post-exposure mechanical performance.

For each exposure condition eight replicates GFRP and CFRP coupons were tested for their tensile strength under displacement-controlled mode at a rate of 1.27 mm/min. Eight replicates of GFRP and CFRP SLB specimens were also tested in displacement control mode for their post-exposure lap shear strength.

3 RESULTS AND DISCUSSION

3.1 FRP Coupons

3.1.1 Gamma Radiation

Figs. 5 and 6 compare the post-exposure strength of GFRP and CFRP coupons with their control counterparts. The figures show that there were negligible changes in the strength of GFRP and CFRP coupons as a result of exposure to 290 kGy of gamma radiation at 38°C.

The exposure, however, caused a change in the colour of the epoxy (Fig. 7). This color change may be accompanied by some changes in the mechanical properties of the epoxy; however, the effects of minor changes in mechanical properties of the matrix do not significantly affect the mechanical performance of a unidirectional composite in the fibre direction. On the other hand, since the matrix had a low glass transition temperature and was exposed to a relatively low dose of gamma radiation, the strength of the matrix may have increased.

3.1.2 LOCA Exposure

No degradation in the strength of the GFRP coupons was observed (Fig. 5). The CFRP coupons exposed to LOCA showed negligible reduction in strength (Fig. 6).

3.1.3 Sustained High Temperature and Temperature Cycling

It was observed (Fig. 5) that sustained high temperatures and temperature cycling had negligible effect on the tensile strength of GFRP. A drop of about 5% in the average strength of the specimens exposed to 65°C and temperature cycling in air was observed. These changes are within the range of the

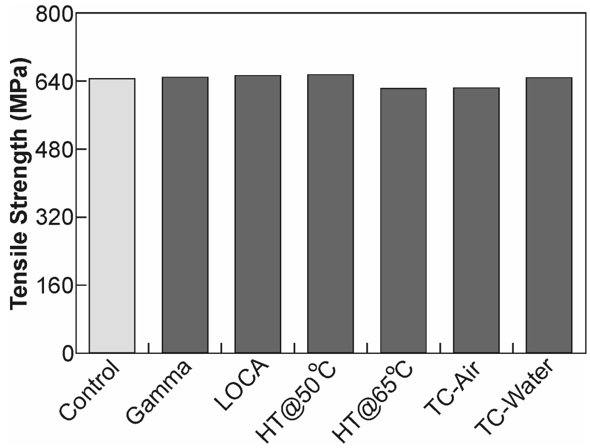

Figure 5: Post-exposure tensile strength of GFRP

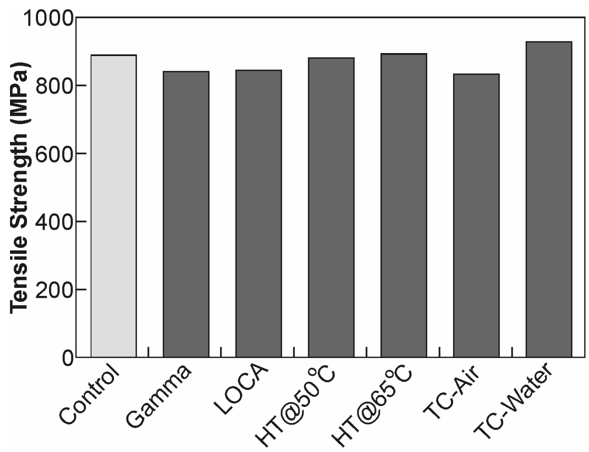

Figure 6: Post-exposure tensile strength of CFRP

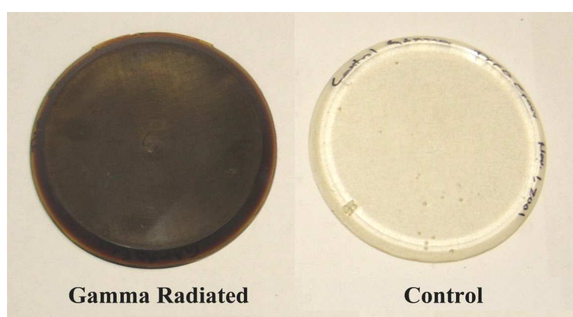

Figure 7: Color change in epoxy exposed to gamma radiation

scatter observed in the strength values of GFRP coupons and are not considered significant.

It can be observed in Fig. 6 that the exposures to high temperature did not have any significant effects on the mechanical properties of CFRP coupons. The lowest average strength was observed in the case of specimens exposed to temperature cycling in air. This drop of about 6% is negligible compared to the observed scatter in the strength data, which was as high as 10%.

Based on the observed results, both GFRP and CFRP materials can be considered to have good resistance to sustained high temperatures and temperature cycling. It should be noted that these specimens were not subjected to any load while exposed to these environments.

3.1.4 Increasing Temperature under Sustained Load

CFRP and GFRP coupons while subjected to stress of about 30% of their respective ultimate strength did not fail in the gauge length region up to a temperature of 110°C. However, due to extreme slippage in the grip region, the load could not be maintained with further increase in the temperature.

3.2 FRP Single Lap Bonded Specimens

3.2.1 Gamma Radiation

Figs. 8 and 9 compare the post-exposure strength of exposed GFRP and CFRP SLB specimens with those of their control counterparts. It was observed that exposure to gamma radiation did not cause any significant adverse changes in strength of the GFRP and CFRP single lap bonds.

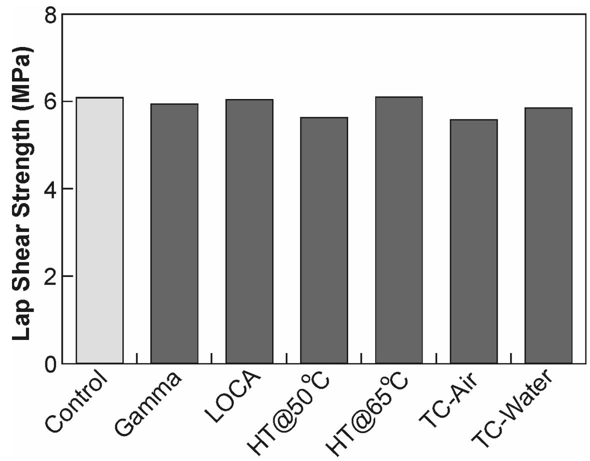

Figure 8: Lap shear strength of GFRP-GFRP

3.2.2 LOCA Exposure

It was observed (Fig. 8) that the exposure did not cause any significant adverse changes to the strength of the GFRP-GFRP bond. However, the strength of CFRP SLB specimens (Fig. 9) decreased by about 18%.

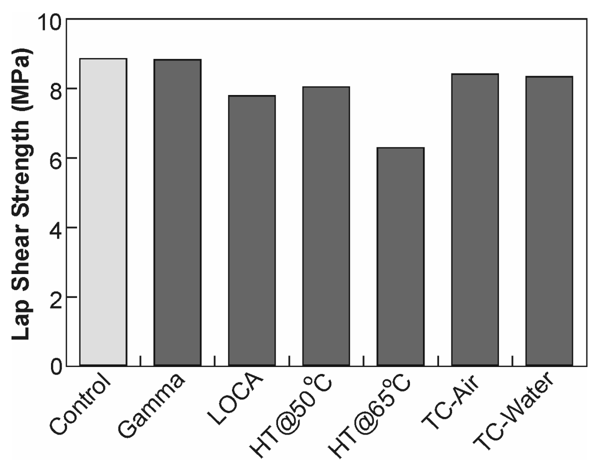

Figure 9: Lap shear strength of CFRP-CFRP

3.2.3 Sustained High Temperature and Temperature Cycling

Fig. 8 shows that the exposure to high temperature and temperature cycling did not cause any significant adverse changes in the average shear strength of the GFRP-GFRP bonds. The lowest average bond shear strength, 92% of the control specimens, was observed in the specimens that were exposed to temperature cycling in air.

The effect of exposure on the strength of CFRP SLB was much more severe than on the GFRP specimens (Fig. 9). Significant deterioration was observed in the CFRP-CFRP bonds exposed to 65°C, where the loss of bond strength was about 30%.

3.2.4 Sustained Load and Increasing Temperature

In the FRP SLB specimens stress between the bonded panels is transferred through the epoxy at the interface in the overlap region. The properties of epoxy, and therefore of the bond is affected by temperature. This section discusses how the GFRP and CFRP bonds behaved when they were subjected to increasing temperature while under stress.

Fig. 10 shows typical responses of GFRP and CFRP SLB specimens subjected to increasing temperature. It can be seen that a stress level of about 2.0 MPa could be maintained to about 63°C followed by a gradual drop in the stress level. At 67°C the stress level dropped to 1.7 MPa, at which point it was readjusted by increasing the actuator's displacement. At 74°C the stress dropped suddenly corresponding to the specimen's failure at the overlap.

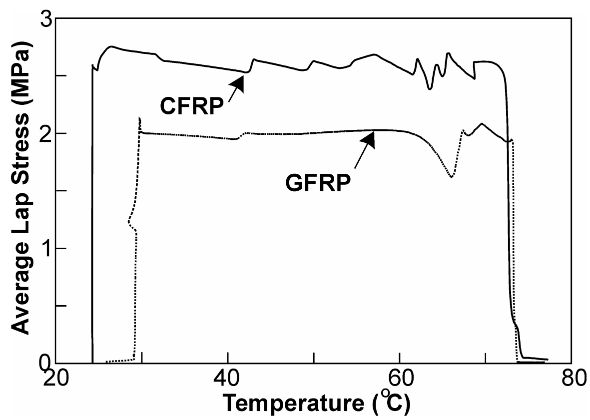

Figure 10: FRP SLB specimens under increasing temperature

The CFRP SLB specimens had a response similar to the GFRP SLB specimens. Fig. 10 shows the stress in a CFRP SLB specimen versus temperature. The stress level of about 2.6 MPa was resisted to about 50°C, beyond which it had to be maintained by adjusting the actuator displacement. At about 72°C no further stress could be resisted by the specimen and a sudden failure occurred at the overlap.

The tests on the FRP SLB specimens under increasing temperature showed that the FRP-FRP bond was susceptible to temperature and could not resist any stress at temperatures higher than about 70°C.

4 CONCLUSION

This experimental work confirmed that up to approximately 290 kGy of gamma radiation had no significant negative effect on the strength of room-temperature-cured FRP coupons and FRP-to-FRP bonds. These materials therefore meet the radiation durability requirements of a typical nuclear power plant[2].

In the case of LOCA, it can be concluded that exposure to 135°C, which is a much higher temperature than the glass transition temperature of the epoxy (80°C), in absence of stress did not cause any significant changes in the post-exposure mechanical properties of GFRP and its bond. LOCA and high temperatures, on the other hand, did affect the post-exposure strength of CFRP-CFRP bond. Overall, however, it can be stated that if GFRP and CFRP materials are exposed to high temperature such as those of LOCA, their post-exposure tensile and bond strengths will not be drastically degraded, as long as they are not subjected to any stresses for the duration of the exposure. When under stress, the FRP-FRP bonds failed at about as 70°C.

5. Acknowledgments

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6. References

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