FIBRE REINFORCED POLYMERS (FRP) MANUFACTURED FOR CIVIL ENGINEERING APPLICATIONS AND EXPOSED TO GAMMA RADIATION AND LOSS OF COOLANT ACCIDENT (LOCA)

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Abstract: Problems associated with the corrosion and deterioration of reinforcing steel in concrete structures have forced the engineering community to look for innovative solutions. In the past couple of decades, the focus has been on fibre reinforced polymers (FRP) as a potential strengthening material in concrete structures. The effectiveness of FRP structural upgrade has been demonstrated repeatedly in short-term laboratory tests and field applications. Consequently, the level of interest in exploring the potential applications of FRP in various types of structures and environments has increased. One of the potential areas of application of FRP is in nuclear power plants (NPPs). However, durability of FRP subjected to the environments of an NPP is a concern, and there is very little research data available to address this concern.

This paper reports the results of a study that evaluated the durability of FRP in an NPP environment. The study involved testing a total of 168 specimens consisting of FRP coupons, FRP-FRP single lap bonded specimens, and FRP bonded concrete prisms for their mechanical performance before and after exposure to gamma radiation and loss of coolant accident (LOCA). Glass and carbon FRPs were included in this study. The specimens were tested for tensile and bond properties. Although, there was some scatter in the rest results, the comparisons of exposed and control specimens showed that the FRP displayed good resistance to the exposures. The tensile and bond properties of FRP were not adversely affected in any significant manner as a result of the exposures.

1. INTRODUCTION

The use of externally bonded fibre reinforced polymers (FRP) to strengthen or rehabilitate existing concrete structures for extending their service life is proving to be an economical solution. This type of application is increasing at a rapid pace, and the effectiveness of FRP structural upgrade has been demonstrated repeatedly in short-term laboratory tests and field applications. The concrete industry's interest in FRP reinforcement is largely due to the fact that FRP does cause durability problems similar to those of steel corrosion. It can also be very advantageous when speed of construction is of high importance. Additionally, the light weight of composite materials can result in substantial labour saving.

FRP sheets and plates have been used to improve the flexural stiffness and strength of concrete beams, slabs, and walls (Meier et al. 1993; Shahawy and Beitelman 1996; Ehsani and Saadatmanesh 1997; Xiao and Rui 1997; Sheikh et al. 2002). They have also been used to wrap reinforced concrete columns to enhance their strength and ductility in resisting seismic loads (Kaliakin et al. 1996; Sheikh and Yau 2002; Iacobucci, Sheikh and Bayrak 2003).

Most FRP products, for applications in repair and strengthening of concrete structures, contain continuous fibres (glass, aramid, or carbon) embedded in a thermoset resin matrix (polyester, vinyl ester, or epoxy) that holds the fibres together and transfers the load between them. The resin also functions as the adhesive between the FRP reinforcement and the concrete substrate. The behaviour and integrity of an FRP-reinforced concrete element depend not only on the properties of individual materials, but also on the performance of the FRP-adhesive and adhesive-concrete interface bonds. There are environmental conditions encountered in civil structures that may affect the mechanical properties of certain types of FRP and the integrity of FRP-to-FRP and FRP-to-concrete bonds.

The experimental data on the durability of FRP in civil engineering applications is very limited, largely because FRP use in civil engineering is relatively new compared to other conventional materials. The research on properties and durability of FRP has been mostly conducted by the aerospace and automotive industries. These industries have significant differences from the construction industry in terms of manufacturing and installation processes, exposure environments and load application mechanisms.

There is great interest in exploring the application of FRP in specialized concrete structures such as nuclear power plants. In these special applications FRP can be exposed to sustained high temperatures, sudden temperature spikes, steam, and gamma radiation. The amount of information available in the public domain on the durability of FRP subjected to the environments of nuclear power plants is limited to non-existent.

This paper evaluates the effects of gamma radiation and LOCA on the FRP's tensile properties and FRP-FRP and FRP-concrete bond properties. Specimens were exposed to the two environments and were tested under static loads for their pre- and post-exposure mechanical performance. Based on the mechanical test results the effects of the exposures on the specimens were quantified.

2. LITERATURE REVIEW

2.1. Gamma Radiation

Changes in the mechanical properties of FRP exposed to gamma radiation have been observed in laboratory tests, as reported by a few researchers. The findings from a selected number of reports from the literature are summarized below. However, these investigations are mostly from the aerospace industry and from super-conducting magnet coils in a fusion reactor with doses of radiation much larger than what is expected to be experienced in the service life of a nuclear power plant. Besides, in those applications, the FRP materials are processed differently and contain resins with properties that are significantly different from the ones used in civil engineering applications. For example, the FRP used in the aerospace industry contains resins that are cured at high temperatures and therefore have glass transition temperatures, Tg, that are generally higher than 200ºC. For the materials used in the present study the Tg is about 80ºC. Durability of polymers in nuclear power plants has been studies, but most of the studies have been on electrical cables (NEA, 1999).

Egusa (1991) also studied the effects of glass transition temperature, Tg, of epoxies on the gamma-radiation resistance of their respective glass-epoxy composites. The epoxies had Tg values of 213ºC and 165ºC. The results showed that the strength of the composite short beams with a Tg of 165ºC increased with increasing radiation at relatively low doses, below 5 MGy, reaching a value comparable to that of the composite with a Tg of 213ºC. Such an increase in strength was not observed in the composite with Tg of 213ºC. He suggested that the strength increase that was observed only in the composite with Tg of 165ºC was probably, at least in part, due to radiation-induced cross-linking in the epoxy network structure. After exposure to doses higher than 5 MGy, identical degradation patterns were observed in both types of composites.

Egusa (1991) studied the effects of up to 220 MGy of gamma radiation in air at room temperature on the performance of E-glass and T-glass epoxy composite short beam specimens. The objective was to determine the influence of fibre type on the durability of FRP. The specimens were tested in three-point bending at -196ºC in liquid nitrogen. Comparison of the degradation behaviour among E-glass and T-glass fabric composites revealed that the observed loss of strength did not depend on the kind of fibre or the type of weave of fabric. The strength loss was due to a change in the ultimate strain of the matrix caused by radiation.

Dispennette et al. (1994) studied the effects of 54.6 Mrad (546 kGy) of gamma radiation on the glass transition temperature (Tg) of postcured and non-postcured carbon-epoxy composite. Only slight changes in Tg were reported. It was also reported that after the radiation, chain scission was the dominant feature of the changes in the post-cured laminates. Cross-linking was reported to be the dominate feature of the changes in the non-post-cured laminates.

There are no reported cases of FRP having been used as reinforcement in nuclear power plants; hence, there are no published codes or test standards for it. However, there are standards that cover the durability of organic materials, mainly coatings and sealants, used in nuclear power plants. ASTM D4082 (2010) covers the effects of gamma radiation on coatings for use in nuclear power plants. It establishes guidelines for evaluating the radiation tolerance of coatings under continuous radiation exposure for the projected lifetime of nuclear power plant. According to this standard, test specimens should be exposed to the radiation at 1x106 rad/h (10 kGy/h) for a total accumulated dose of 1x109 rads (10 MGy), unless otherwise specified by the owner. The specimens may be in air or water depending on the intended application of the material.

CSA Standard N287.1 sets the requirements for radiation resistance of liner materials used in CANDU containment structures. Accordingly, the effects of gamma radiation in air on the physical properties of each constituent material of the complete liner system shall be determined as follows:

1. a test shall be performed on a sample specimen of the liner material applied to a concrete substrate whose minimum dimensions are 75 x 50 x 6 mm,
2. exposure to radiation shall be in a gamma cell at a temperature of 32°C and a dose rate of $1.8\text{x}10^6$ rad/h (18 kGy/h), and
3. the minimum test dosage of radiation shall be equal to the specified maximum accumulated dosage predicted for the life of the plant.

Accumulated does level for CANDU containments are much lower than what is required by ASTM D4082. Ontario Hydro Technologies (OHT, 2003) specified that for materials to be used in a containment structure of nuclear power plants, they have to be tested for their durability to a minimum dosage of 200 kGy of nuclear radiation. This value represents a “safety factor” of four based on the information for Reactor Building 1 at Pickering Nuclear Generation Station, which reportedly has a maximum lifetime dosage of approximately 50 kGy, including a postulated accident. The maximum dosage of 250 kGy represented an upper bound.

The Atomic Energy of Canada Ltd. (AECL) has applied up to 400 kGy of gamma radiation for testing various types of organic components, such as cables, seals, etc. that are used in nuclear power plants (NEA, 1999).

Smith (1971) reported that in 1965 Ontario Hydro issued invitations to nine suppliers of Canadian manufactured and commercially available coatings to submit samples for testing. Eighteen samples of vinyl and epoxy were received and tested. It was reported that the best epoxy system showed excellent radiation resistance and could be used for up to 1000 Mrad (10 MGy).

Freyssinet (2004) reported that exposure to 250 kGy of ionizing radiation of the carbon reinforced fabric (TFC®) used for strengthening of concrete structures caused no significant defect in the materials. TFC consists of carbon fibre and epoxy. The composite has an ultimate tensile strength of 1700 MPa and a tensile modulus of 105 GPa.

2.2. Loss of Coolant Accident

Browning (1977) studied the mechanism of losses in the mechanical properties of structural epoxy with glass transition temperature, Tg, of 177°C at elevated temperature after exposure to high humidity environments. In specimens that had reached moisture equilibrium thermal spikes caused further increase in the moisture content. It was argued that development of cracks and micro-cracks following the thermal spike was responsible for moisture pick-up after the initial equilibrium moisture level. This increase in moisture gain was accompanied by an increase in thickness of the specimens. After drying, the specimens had residual thickness increase of about 1.75%. Browning concluded that in humid environment the mechanical properties of epoxy resin degraded due to plasticization, and when the specimens with high moisture content were exposed to high temperatures, swelling took place due to micro-cracking and subsequent acceleration in moisture gain.

Misaki and Iwatsu (1985) studied the effects of boiling water on flexural strength of chopped strand mat-polyester laminates and tensile strength of unreinforced polyester resin. Four types of polyester were reinforced with chopped glass mat by a hand-lay-up technique and post cured at 100°C for 2 hours. The losses in flexural strength of the composites and tensile strength of the resins for each type of polymer corresponded to their level of weight gain due to moisture absorption. In the tested specimens the weight gain ranged from 0.7% to 3.3% and the corresponding loss of strength range from 20% to 60%.

Collings and Stone (1985) studied the damaging effects of temperature, moisture, and thermal spiking on carbon fibre epoxy composites. The specimens were cured in an autoclave for about 200 minutes at 185°C and then post-cured in an air-circulating oven for 12 hours at 185°C. The specimens were divided into the following groups:

1. Dry as manufactured
2. Dried at 60°C under vacuum
3. Conditioned at 60°C and 94% relative humidity (R.H.)
4. Dried at 60°C under vacuum and subjected to 24 (135°C) thermal spikes
5. Conditioned at 60°C and 94% R.H. and subjected to 24 (135°C) thermal spikes

The 135°C thermal spikes were for 3.5 minutes each in an air-circulating oven. After each spike the specimens were weighed and returned to their respective environments. The spikes were applied at intervals of 2 or 3 days. After the exposures, short beam tests were conducted to determine the post-exposure room temperature strength of each group of specimens. The specimens were also examined under optical microscope for evidence and size of cracks.

Collings and Stone concluded that conditioning at a temperature of 60°C and in a dry condition had no damaging effect on the laminates. Conditioning at 60°C and 96% R.H. reduced the strength of the specimens. After 256 days of exposure the strength had fallen to 83% of its dry strength. Thermal spiking of dry laminates at 135°C produced no visible degradation. A drop of about 7% in the strength was, however, observed. The thermal spiking of 135°C of laminates containing moisture produced permanent damage in the form of inter-laminar cracks. As a result the equilibrium moisture level almost doubled and the room temperature strength reduced to 75% of its dry strength.

Stansfield and Pritchard (1989) studied damage generation and healing during composite thermal spikes. They used 16-ply graphite/epoxy composite laminates that were cured at 175°C in an autoclave followed by a post-cure at 190°C for 14 hours. Saturated specimens that were conditioned in a humidity chamber (96% r.h.) were subjected to thermal spikes of 135°C in a specially prepared oven, at which they were kept for either 5 minutes or 870 minutes (14.5 hours). Some of the specimens that were subjected to 5-minute spikes were subjected to a second spike after one further week in the humidity chamber. The second spike was either 5 or 870 minutes long.

The specimens subjected to one 5-minute spike showed more damage than the ones subjected to one 870-minute spike. It was suggested that a substantial part of the damage was caused by contraction onto redistributed moisture during cooling. It was observed that the damage created during heating was repaired during the long-term stay at 135°C.

Buggy and Carew (1994) studied the effects of thermal aging on CFRP by subjecting it to high temperatures (120, 250, and 310°C) for up to 76 weeks and testing them in three-point flexure. It was reported that thermal aging at 120°C did not change the static flexural strength or modulus. At 250°C the static flexural strength remained unchanged for about 16 weeks, but further aging caused dramatic loss in strength. Based on the gravimetric and microscopic examination, it was concluded that matrix degradation was the controlling factor causing the abrupt reduction in mechanical properties. Continued thermal aging caused further matrix degradation and, consequently, reduction in mechanical properties. Thermal aging at 310°C caused rapid and extensive matrix degradation and correspondingly large decreases in mechanical properties.

3. EXPERIMENTAL PROGRAM

The material, specimens, equipment and test setup that were used to evaluate the post-exposure mechanical response and durability of FRP are described in this section.

3.1. Materials

3.1.1. Fibres and Matrix

Commercially available glass and carbon fabrics and epoxy are the components of FRP sheets used in this investigation. The properties of the hand lay-up composites as provided by the supplier are shown in Table 1. The fabric comes in the form of unidirectional woven rovings. The main rovings, which carry the applied loads, are aligned in the longitudinal direction, 0°, and are held together by non-structural aramid wefts in the transverse direction, 90°. The epoxy system is a two part resin (A and B) that are mixed together in a ratio of 100:42, respectively, using a mechanical mixer.

Table 1. Properties of TYFO™ S Fiberwrap™ System CFRP and GFRP

Property	Carbon (SCH 41) FRP	Glass (SHE 51) FRP
Ultimate Tensile Strength (N/mm)	867	575
Tensile Modulus of Elasticity (kN/mm)	72.4	26.1
Rupture Strain (mm/mm)	0.012	0.022
Nominal thickness of the Fabric (mm)	1.0	1.3
Weight of FRP Sheet (grams/m^2/layer)	1660	2500

3.1.2. Concrete

The concrete used for the specimens had average 28-day strength of about 50 MPa. The void ratio, density and the slump of each mix were measured and found to be reasonably consistent throughout the experimental program. The details of the concrete mix are given in Table 2.

Table 2: Concrete mix proportions and properties

Mix Proportions	Aggregate cement ratio	(by weight)	5.26
	Water cement ratio	(by weight)	0.38
	Air entrainment admixture (AEA)	ml/kg cement	0.03
	Super-plasticizer (SP)	ml/kg cement	5.00
Physical Properties	Density (fresh)	kg/m^3	2470
	Slump	mm	140
	Nominal Compressive Strength	(MPa)	50

3.2. Specimens

The following three types of specimens were used:

1. FRP tensile coupon (Figure 1), 64 specimens;
2. FRP single lap bonded (SLB) specimen (Figure 2), 64 specimens; and
3. FRP bonded concrete prism (Figure 3), 40 specimens.

Carbon fibre reinforced polymer (CFRP) and glass fibre reinforced polymer (GFRP) coupons were used to evaluate the effects of the exposures on the tensile strength, stiffness, and strain at failure of the material. The SLB specimens were used to evaluate the effects of the exposures on the mechanical properties of FRP-to-FRP bonds. The FRP-bonded concrete prisms were used to evaluate the effects of exposures on the mechanical properties of FRP-concrete bond.

3.3. Specimen Preparation

3.3.1. FRP Coupons

The 25 x 175 mm FRP coupons (Figure 1) were made in accordance with the ASTM D 3039. Carbon or glass sheets of 175 x 500 mm and glass sheets of 50 x 500 mm were cut from the rolls of fabric. The 175 mm dimension is the length of the coupons, where each coupon has a 75 mm test region and two 50 mm tabs at each end. The main fibres run along the 175 mm length of the sheets. The 50 x 500 mm glass sheets were used for the tabs of both CFRP and GFRP panels, since glass costs less than carbon.

The sheets were impregnated with epoxy resin, where the resin was applied from both faces of the fabric using a roller brush. Then, the sheets were put together and were pressed with the roller brush to get rid of air bubbles and excessive epoxy. Each assembly (panel) was cured for seven days at room temperature. Panels for each exposure were cut into two half-panels of 175 x 250 mm using a band saw. One half-panel was exposed to gamma radiation or LOCA while the other half-panel was kept at room conditions to be used for making control specimens. To avoid the edge effects in the exposed specimens, the panels were not cut into 25 mm wide coupons until after the exposure. After the exposure, strips of approximately 20 mm wide were cut from the two edges of each exposed panel and were discarded. Eight replicate specimens were obtained from the remaining middle portion of each exposed panel. Eight 25 mm wide coupons were cut from the control half-panels after the seven days of curing.

3.3.2. FRP Single Lap Bonded (SLB) Specimens

The 25 x 300 mm SLB specimens (Figure 2) for testing mechanical properties of FRP-to-FRP bond were prepared in accordance with ASTM D3163. Glass and carbon fabrics were cut into sheets of 200 x 500 mm (A, the main panels) and 90 x 500 mm (B, the tab). The rovings ran along the 200 and 90 mm dimensions of the sheets. The sheets were impregnated separately and then were put together to form the SLB's panels. Sheets A and B were placed side by side on a flat board as shown in Figure 4 with a distance of 10 mm between them. The second sheet A was placed on the top overlapping the first sheet A by 100 mm, bridging the 10 mm gap and extending over the sheet B. The second sheet B was placed on the first sheet A beside the second sheet A with a distance (gap) of 10 mm. The reason for keeping the gap down to 10 mm was to control the sag of the wet fabric, thus, preventing misalignment and kink in the specimens. The panels for each exposure were cured for 7 days at room temperature. The panels were cut into two half-panels of 300 x 250 mm. One half-panel was subjected to gamma radiation or LOCA while the other half-panel was kept at room condition to be used for making control specimens. After the exposures, eight 25 mm wide FRP SLB specimens were obtained from each half-panel. The required numbers of 25 mm wide control specimens were cut from the control half-panels after the seven days of curing.

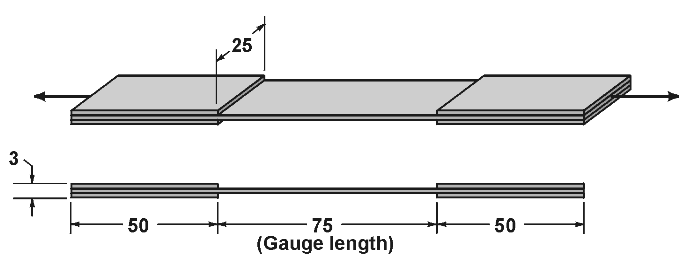


Figure 1. FRP tensile test coupon

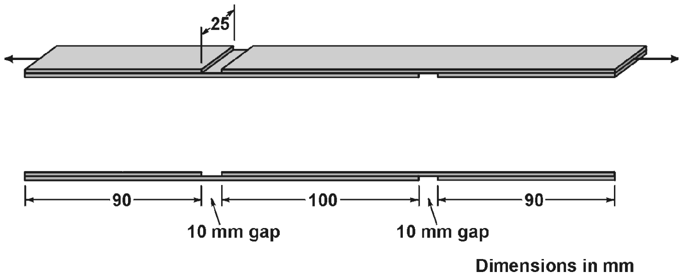


Figure 2. Single lap bonded (SLB) specimen

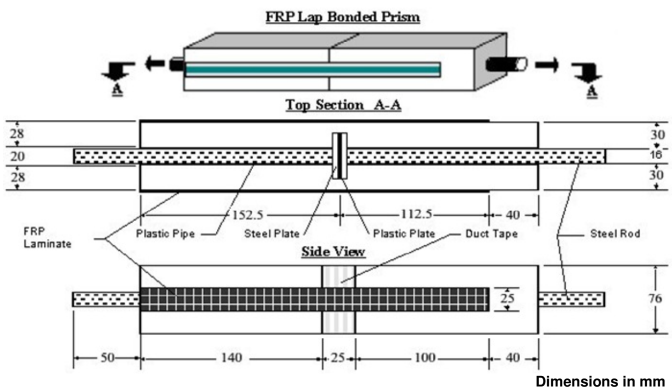


Figure 3. FRP bonded concrete prism

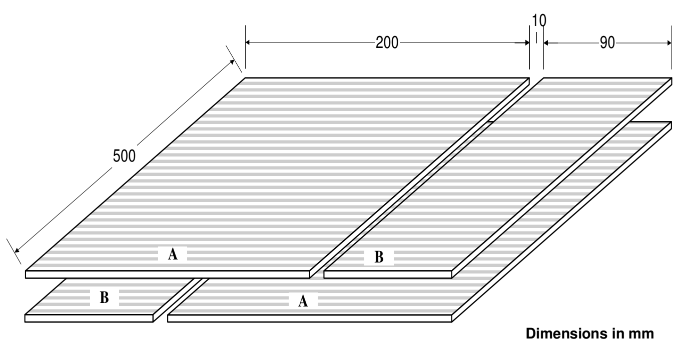


Figure 4. FRP panel for single sap bonded specimens

3.3.3. FRP Bonded Concrete Prisms

Durability of FRP-to-concrete bond was studied using 76 x 76 x 305 mm concrete prisms. The prisms were cast in Formica-laminated wooden moulds. Five specimens could be cast simultaneously in each of the moulds as shown in Figure 5. Each specimen comprised of two 76 x 76 x 152.5 mm concrete prisms held together by two 25 mm wide x 265 mm long FRP laminates bonded on two opposite faces of the prisms (Figure 3).

In each half of the specimens a welded bolt-plate assembly (Figure 6) was installed before casting, which provided the means for load application without causing direct tension in the concrete. The bolt was 15.8 mm in diameter and about 203 mm long, and the plate was 50 x 50 x 6.25 mm. Six 12.5 x 12.5 x 12.5 mm hard plastic spacers were glued in the centre of the sidewalls and the bottom of the moulds to support and centre the bolt-plate assembly (Figure 5). Concentrically placed plastic pipe sleeves, 150 mm long x 19.4 mm in diameter, were used to prevent bond between the bolts and the concrete. To break the bond between the two halves of the prism, a 1 mm thick by 50 x 50 mm square Formica plate was oiled and inserted between the two steel end-plates. The free ends of the bolts were fastened by steel nuts to prevent the inward sliding of the bolts during the casting and vibration. Outward sliding was prevented by putting stiff steel angles on the bolt ends and clamping them together (Figure 7). The rims (top edges) of the moulds were covered with duct tape and the walls were oiled.

The concrete was mixed in accordance with a standard mixing procedure. The moulds were filled with concrete and vibrated long enough to get the air bubbles out but stopped before any segregation could take place. The specimens in the moulds were covered with wet hemp cloth and plastic sheets.

Figure 5. Moulds for the prisms

Figure 6. Steel bolt-plate assembly

Figure 7. Moulds ready for casting

On the following day all the specimens were demoulded and the prisms were stored in a moist room for (28-day) curing. At the end of 28 days the prisms were taken out and air-dried at room temperature. Afterwards, the two side-faces of the prisms where the FRP sheets were to be bonded were sand blasted to get rid of the weak surface and to obtain a uniform bond surface for all the prisms. Figure 8 compares the concrete surfaces before and after sand blasting.

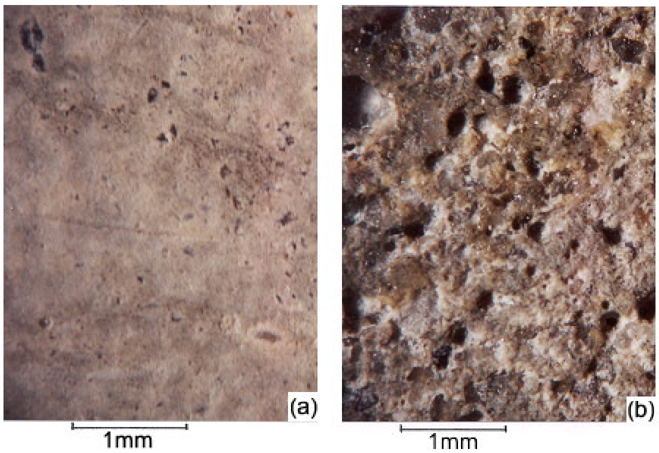


Figure 8. Surface of concrete (a) before sand blasting and (b) after sand blasting.

Lines were drawn on the sand-blasted faces of the prisms to mark the location where the FRP strips were to be bonded. At the mid length of the 305 mm long prism, where the two 152.5 mm long halves were designed to separate, a 25 mm wide smooth-surface duct tape was wrapped around the prism section (Figure 3). The purpose of the tape was to break the bond between the FRP and concrete at and on the two sides of impending crack.

Carbon or glass fabric sheets were cut for the number of prisms to be reinforced. The fabric sheets were laid on thin polyethylene plastic sheets and were impregnated from both faces with epoxy. They were then cut into strips of 25 mm wide x 265 mm long parallel to the main fibre rovings. The previously marked, 25 mm wide strips on the sides of the prisms were coated with epoxy and were left to get tacky. The carbon or glass impregnated strips were then placed on the epoxy coated sides of the prisms and pressed hard to hold uniformly in place. It should be noted that tack-coat epoxy, which is a thicker epoxy for overhead applications, was not used. Tack-coat is not a requirement unless there is difficulty in keeping the sheets on the concrete surface until the epoxy sets. The FRP-bonded prisms were left for one day to cure. The next day the polyethylene backings were stripped off, and the top of the FRP strips were given another coat of epoxy. The prisms were left to cure for six more days, grouped into batches of exposed and control, and were subject to environmental exposure or kept in room condition as control sets, respectively.

3.4. Test setup

FRP Coupons (Figure 1) and SLB specimens (Figure 2) were tested using an Instron testing machine with mechanical grips (Figure 9). The tests were conducted in displacement control mode at a rate of 1.27 mm/min. A mechanism was constructed, and added to the testing system, which measured the elongation of the specimen with a pair of LVDT's as shown in Figure 9. The average values of the two LVTD's were used in the data analysis. The data was recorded using a digital data acquisition system that was powered and controlled by a PC.

The FRP bonded concrete prisms were tested using the SATEC testing machine that was computer-controlled and hydraulically-loaded. Each specimen was connected to U-joints which, in turn, were connected to threaded rods held by machine's grips (Figure 10). The load was applied in a displacement control mode at a rate of about 1.27 mm/min. C-clamps were used to further secure the longer length of FRP panels in the half of the specimen that was not instrumented and was not intended to fail. The force was measured by the machine's load cell, and the bond slips were measure with LVDT's mounted on two sides of each specimen with shorter FRP bond length that was design to fail. Figure 11 shows a typical stress-slip response of FRP-bonded concrete prisms.

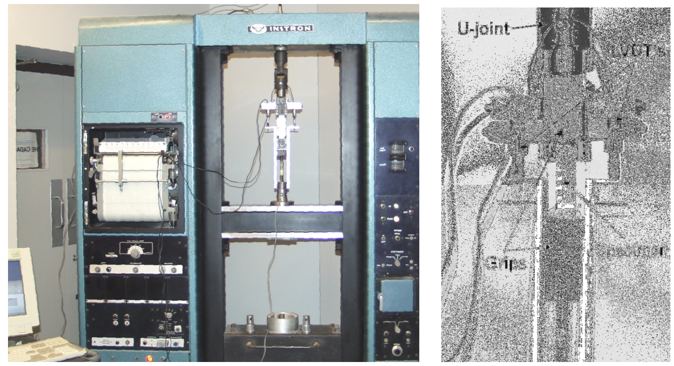


Figure 9. Instron testing machine and the LVDT setup for elongation measurement

3.5. Environmental Exposure

3.5.1. Gamma Radiation

Gamma rays are emitted after the decay in a radioactive element which gets rid of its excess energy by emitting electromagnetic radiation. Since gamma rays lose their energy slowly, they can travel a long distance before they come to a stop. Depending on their initial energy, gamma rays are reported to travel in air from one meter to hundreds of meters and can easily go right through people (Idaho 2004). Since gamma rays have no mass or charge, they are difficult to be blocked and are reportedly a big problem around reactors.

The gamma radiation exposure was conducted at the facilities of ISOMEDIX Corporation (Whitby, Ontario). The specimens were delivered to be exposed to a minimum dose of 25 Mrad (250 kGy) of gamma radiation at 38°C. The source of radiation was Cobalt-60. The dose of gamma radiation was measured by a "Harwell Red 4034" dosimeter. The FRP panels for the coupons and the SLB specimens were irradiated for about 72 hours, and the FRP-bonded concrete prisms were irradiated for about 104 hours. Table 3 lists the number of specimens and radiation dose applied to each type of specimen.

After the exposure to gamma radiation, the specimens were tested at room condition for their post-exposure mechanical performance along with their control counterparts. Results from the tests are presented in the following section.

Table 3: List of specimens exposed to gamma radiation

Specimen Type		Num. of Specimens	Radiation Rate (kGy/hr)	Radiation Duration (hours)	Radiation Total Dose (kGy)
CFRP	Coupons	8	4.04	72.1	291
	SLB Specimens	8	4.04	72.1	291
	Prisms	5	2.93	104.1	305
GFRP	Coupons	8	4.04	72.1	291
	SLB Specimens	8	4.04	72.1	291
	Prisms	5	2.93	104.1	305

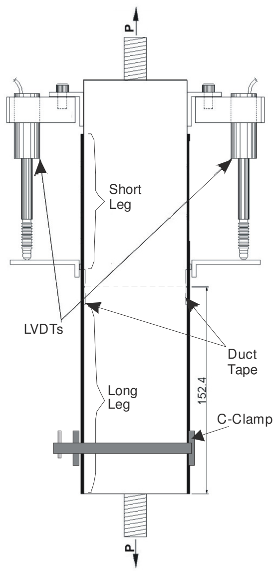


Figure 10. FRP concrete prism in the testing machine.

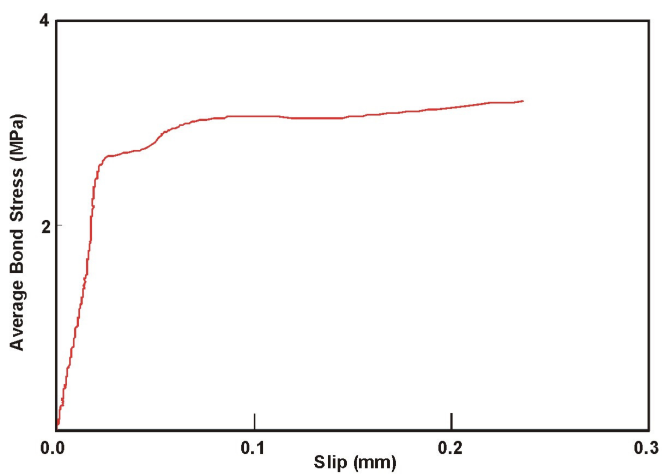


Figure 11. Typical lap shear stress-slip response of a typical FRP bonded concrete prism

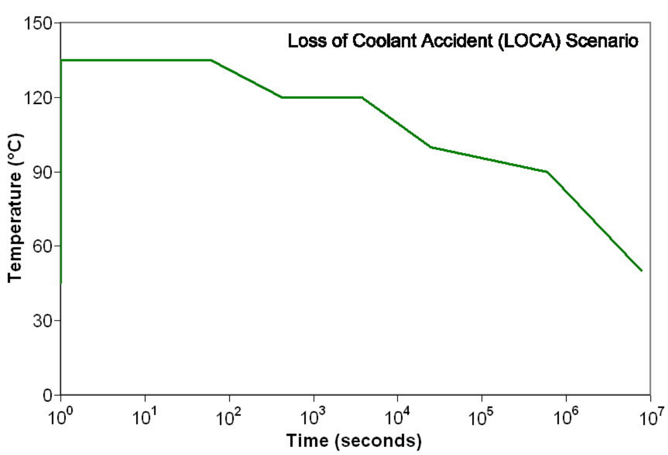


Figure 12. The LOCA scenario used for testing the durability of FRP and CFRP-concrete composites

The LOCA scenario used for the exposure of the specimen in this study is one of the scenarios used by Ontario Power Generation as a measure to qualify organic materials, such as epoxies, for use in nuclear power plants. This LOCA scenario was mainly an exposure to temperature increase without the presence of steam. The LOCA temperature profile is shown in Figure 12. The specimens were placed in an oven that was controlled by a computer system. The oven was programmed to attain the prescribed temperature and change the temperature at a constant rate. The rate of change of temperature was programmed to follow the profile shown in Figure 12.

After about three months of exposure to the LOCA scenario, the specimens were retrieved and tested for their residual mechanical properties at room temperature. The test results are presented in the following section.

4. RESULTS AND DISCUSSION

4.1. Gamma Radiation

4.1.1. FRP Coupons

Figure 13 compare the post-exposure tensile properties of GFRP and CFRP coupons exposed to gamma radiation to their control counterparts. The results show that changes in the strength and modulus of elasticity of GFRP and CFRP coupons as a result of exposure to gamma radiation were negligible. The slight differences in the peak strain values of exposed and control sets are within the range of scatter in the data. The differences in peak strain can also be attributed to higher slippage of some specimens in the grip at loads levels close to failure. Overall, it can be concluded that the residual mechanical properties of GFRP and CFRP coupons tested in this study are unaffected by exposure to up to 290 kGy of gamma radiation at 38°C.

The exposure, however, caused a change in the colour of the epoxy (Figure 14). Figure 15 shows examples of GFRP and CFRP coupons that were exposed to gamma radiation. The colour change is more evident in GFRP because of the composite’s lighter colour. This colour change may be accompanied by some mechanical changes in the matrix; however, the effects of small changes in the mechanical properties of the matrix do not manifest themselves in the tensile strength of unidirectional composite tested in the fibre direction. On the other hand, because the matrix had a low glass transition temperature (80°C) and was exposed to a relatively low dose of gamma radiation, the strength of the matrix is expected to have increased slightly.

4.1.2. FRP Single Lap Bonded (SLB) Specimens

Figure 16 compares the post-exposure mechanical responses of GFRP and CFRP SLB specimens exposed to gamma radiation with those of their control counterparts. It was observed that exposure to gamma radiation did not cause any significant adverse changes in the strength and maximum slip of the bond. The strength of CFRP SLB specimens showed an increase of about 8% which is within the range of scatter of the strength values of control and exposed specimens and it can therefore be considered negligible. The same applies to bond slip values. The effect of exposure on the mechanical properties of GFRP SLB specimens was also negligible.

4.1.3. FRP-Bonded Concrete Prisms

Figure 17 compares the average post-exposure bond strength and lap slip of GFRP- and CFRP-bonded concrete prisms exposed to gamma radiation with those of their control counterparts. There were no changes in the strength or amount of slip in the CFRP-concrete bonds. The slight drop that is observed in strength of GFRP-concrete bond and a slight increase in their corresponding bond slip are considered small.

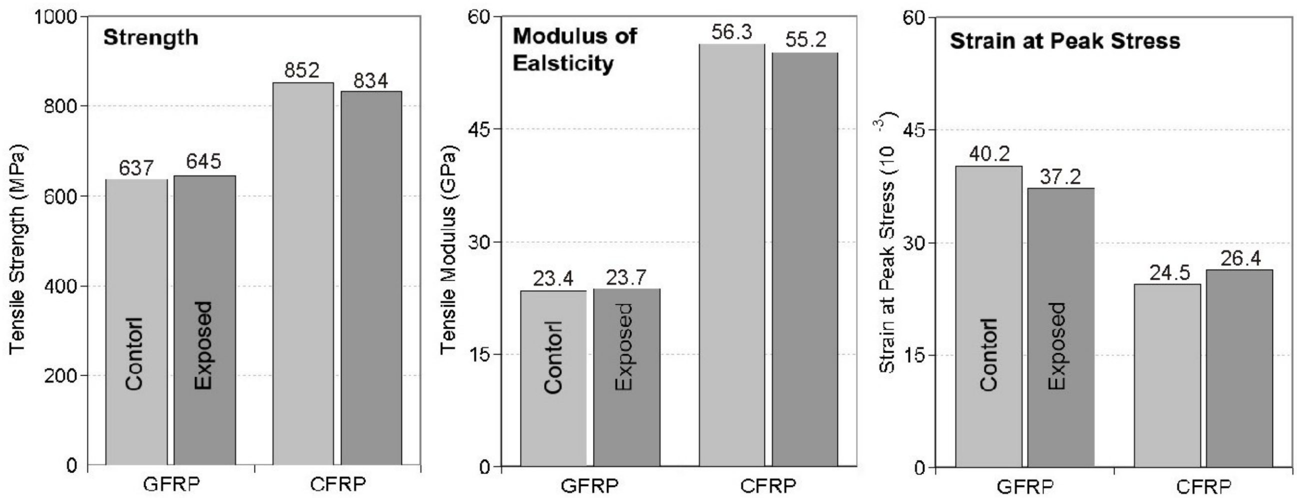


Figure 13. Comparing the effects of gamma radiation on the tensile properties of FRP

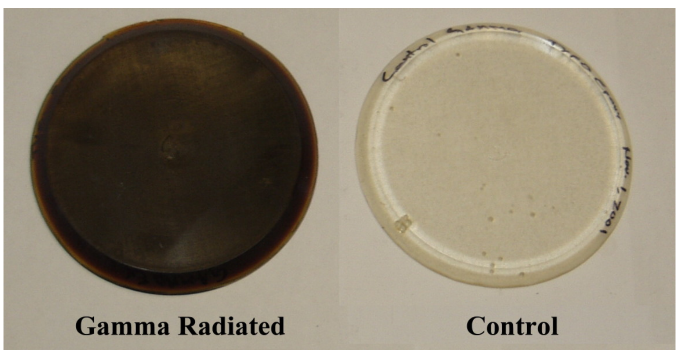
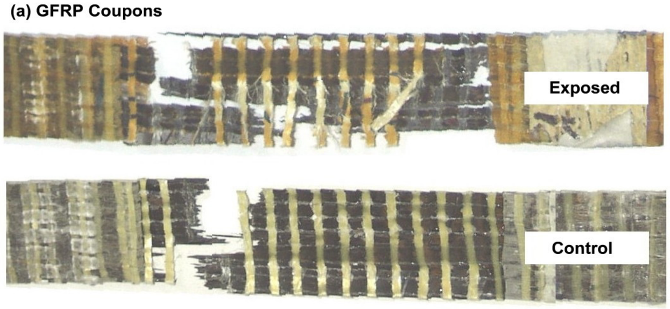


Figure 14. Color change in epoxy caused by about 290 kGy of gamma radiation

(a) GFRP Coupons



(b) CFRP Coupons

Figure 15. Comparing the color of GFRP and CFRP coupons exposed to gamma radiation with their control counterparts

4.2. Loss of Coolant Accident

4.2.1. FRP Coupons

Figure 18 compares the post-exposure tensile properties of GFRP and CFRP coupons to their control counterparts. No degradation in the strength or modulus of elasticity of the GFRP coupons was observed. The slight increase in the value of strain at peak stress is within the range of the experimental scatter.

The CFRP coupons exposed to LOCA when compared to their control counterparts showed reduced strength and modulus of elasticity of about 12% and 19%, respectively. However, this difference is more due to higher than normal strength and modulus values of the control specimens and not necessarily due to degradation of CFRP.

4.2.2. FRP Single Lap Bonded (SLB) Specimens

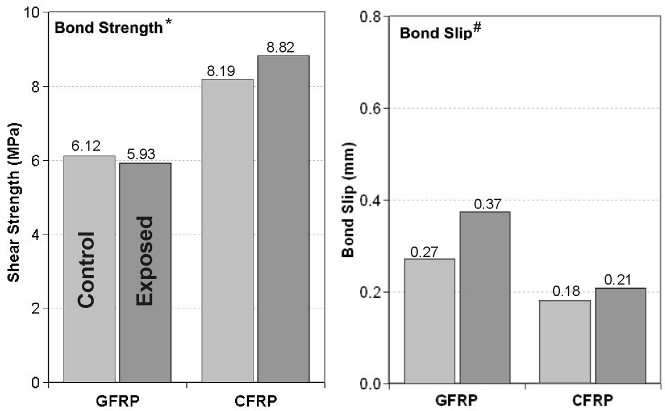
Figure 19 compares the post-exposure mechanical response of GFRP and CFRP SLB specimens subjected to LOCA to their control counterparts. It was observed that the exposure did not cause any significant adverse changes to the strength of the GFRP-GFRP bond. However, a reduction of about 11% in stiffness and an increase of about 16% in the bond slip of GFRP SLB specimens were observed.

The strength of CFRP SLB specimens decreased by about 18%. Their average stiffness dropped by about 22%. The mechanism that caused these changes cannot be explained with the available data. The reduction in strength is a combination of higher than normal strength of control specimens and potential degradation of the bond at the microscopic level. However, detailed micro-mechanical experimental and analytical evaluation of the changes was not in the scope of this study. The effect of LOCA exposure on the amount of slip at peak load (ductility) is negligible; corresponding to the proportional decrease of the average strength and stiffness of CFRP SLB specimens.

4.2.3. FRP-Bonded Concrete Prisms

Figure 20 compares the post-exposure bond strength and lap slip of the exposed FRP bonded concrete prisms to those of their control counterparts. A significant increase in the strength of GFRP-bonded concrete prisms exposed to LOCA was observed. When compared with their control counterparts, the exposed specimens had on average about 35% higher strength. However, it should be noted that the average strength of the control specimens is lower than the strength of GFRP-concrete bonded prisms in other, similar tests. For example, the control specimen for the gamma exposure had average bond strength of about 1.66 MPa (Figure 17). If the strength of gamma-control specimens was used for comparison, the average increase in bond strength due to LOCA exposure would be about 8%.

There was no significant change in the average bond strength of the CFRP-concrete bonds. However, overall the CFRP specimens showed great variability and scatter; therefore, the bond stiffness and amount of bond slip at peak load could not be used to quantify the effects of the LOCA exposures.



* Bond strength values are averages of eight specimens
\# Bond slip values are based on averages of four specimens

Figure 16. Comparing the effects of gamma radiation on bond properties of GFRP and CFRP single lap bonded specimens

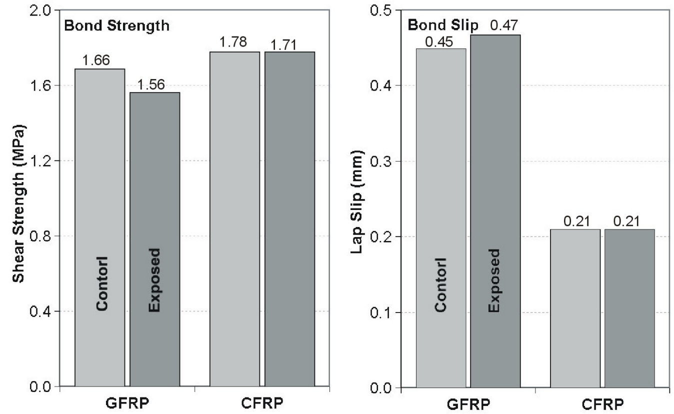


Figure 17. Comparing the effects of gamma radiation on bond strength and slip of GFRP and CFRP bonded concrete prisms

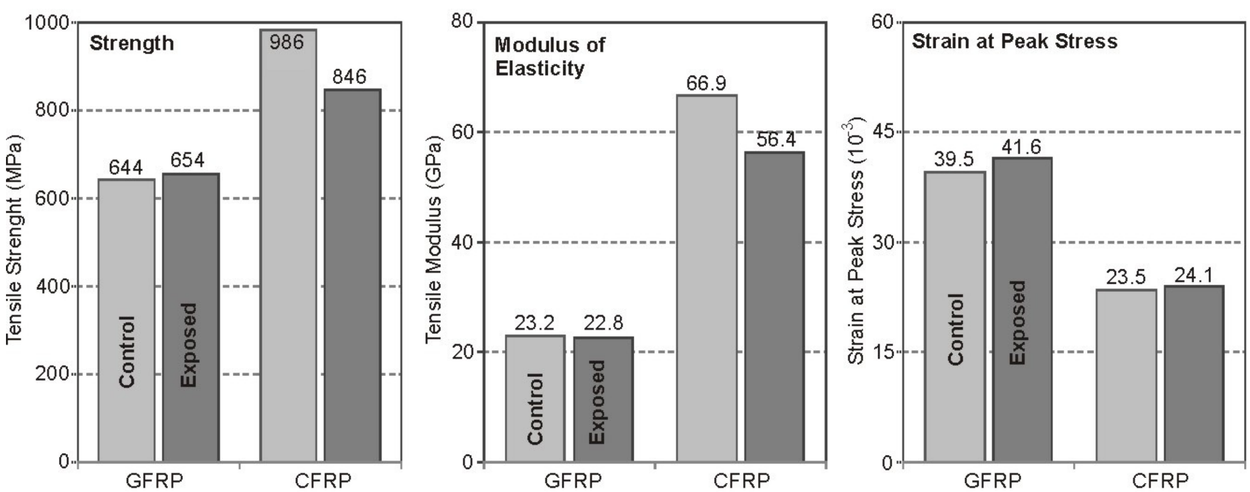
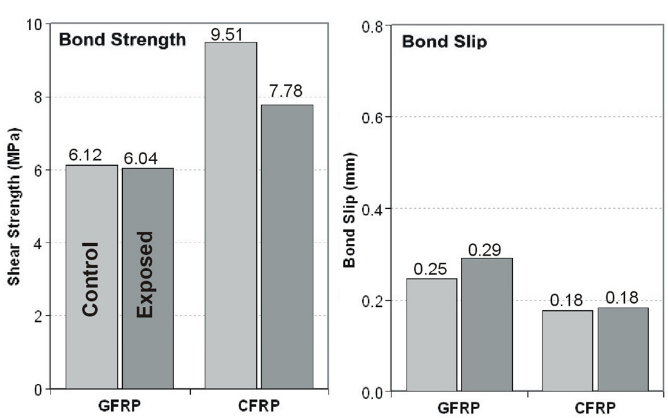


Figure 18. Comparing the effects of LOCA on the tensile properties of FRP.



* Bond strength values are averages of eight specimens
\# Bond slip values are based on averages of four specimens

Figure 19. Comparing the effects of LOCA on bond properties of GFRP and CFRP single lap bonded specimens

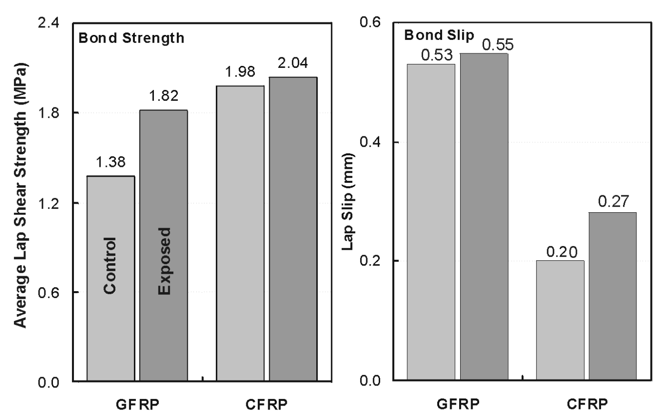


Figure 20. Comparing the effects of LOCA on bond strength and slip of GFRP and CFRP bonded concrete prisms

5. CONCLUSIONS

The durability of FRP and its bonds subjected to gamma radiation was evaluated. CFRP and GFRP coupons, CFRP and GFRP single lap bonded (SLB) specimens, and CFRP- and GFRP-bonded concrete prisms were tested under static loads for their resistance to the level of gamma radiation that is expected in a life time of a typical CANDU power plant containment structure. Although, there is scatter in the test results, especially in the case of CFRP, the experimental results showed that up to about 300 kGy (291 kGy for coupons and SLBs and 305 kGy for prisms) of gamma radiation did not have any significant effect on the strength of room-temperature-cured FRP, FRP-FRP bonds, and FRP-concrete bonds. The average changes in tensile strength of GFRP and CFRP coupons were +1% and -2%, respectively; the average change in the strength of GFRP and CFRP single lab bonds were -3% and +8%; and the average change in the strength of GFRP- and CFRP-concrete bonds were -6% and -4%.

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 the absence of stress did not cause any significant changes in the residual mechanical properties of GFRP and its bonds. LOCA, however, did adversely affect the post-exposure strength and stiffness of CFRP coupons and CFRP-CFRP bond when compared to their control counterparts. The average changes in tensile strength of GFRP and CFRP coupons were +2% and -14%, respectively; the average change in the strength of GFRP and CFRP single lab bonds were -1% and -18%; and the average change in the strength of GFRP- and CFRP-concrete bonds were +32%% and +3%.

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