EFFECT OF COMBINED ENVIRONMENTAL CYCLES ON RC COLUMN WRAPPED WITH FRP SHEET

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ABSTRACT

As a part of an extensive research program on structural integrity evaluation of RC columns retrofitted with FRP wraps, this study aims to investigate the effect of combined environmental conditions consisting of freeze-thaw cycles, high-temperature cycles combined with ultraviolet radiation, and high-humidity cycles, on reinforced concrete (RC) columns wrapped with FRP sheet. Full-scale and small-scale RC columns were strengthened with two types of FRP sheet (CFRP and GFRP), which are widely used in the field of column strengthening. The columns were subjected to five different environmental conditions: room temperature, freeze-thaw cycles (under dry condition and soaked in saline solution), and combined environmental cycles (under dry condition and soaked in saline solution). Results include the stress-strain relationships obtained through uni-axial compression test aimed to evaluate the potential degradation the strength and ductility resulting from the effects of environmental exposure.

Results show a slight decrease in the ultimate strength of RC columns due to the freeze-thaw cycles and combined environmental cycles, which may be attributed mainly to the degradation of concrete itself due to the freeze-thaw cycles rather than FRP sheet. Results also show a significant decrease in ultimate axial strain of both CFRP and GFRP wrapped column due to the freeze-thaw and combined environmental cycles. Furthermore, the reduction in ultimate radial strain of the small-scale column wrapped with CFRP was larger than those of similar specimen wrapped with GFRP sheets. The GFRP wrapped RC column was affected by the saline solution more than CFRP wrapped RC column.

KEYWORDS: environmental condition, freeze-thaw cycles, fiber reinforced polymer sheet, reinforced concrete column, saline solution, strength, strain, uni-axial compression test

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1. INTRODUCTION

In recent years, FRP composite materials have shown to be an efficient solution for repair and rehabilitation of structurally deficient RC structures. Through full-scale and field tests, application, FRP composite jackets have demonstrated to be effective replacement for the conventional steel jacketing for the seismic retrofit and repair of damaged RC columns [1-3]. In parallel, extensive analytical works have been conducted to estimate the confinement effect of FRP composite on the concrete [4-7]. However, the long-term performance and durability of RC columns strengthened with FRP composite materials is not fully understood

In most cases, RC structures strengthened with FRP sheets are exposed to harsh environments such as wide temperature and humidity fluctuations, rain and snow, and even freeze-thaw conditions, which could be aggravated by the use of deicing salt throughout their service life. Particularly, the subzero temperatures, similar to those frequently seen in North America, in combination with freeze-thaw conditions may result in a significant change in the thermo-mechanical properties of FRP composite materials. It was shown that unidirectional tensile strength of FRP composite materials could be decreased at low temperatures ranging from -10 °C to -40 °C probably due to the matrix hardening [8]. It was also reported that although there is a degradation in the ultimate strength and strain of the concrete confined with FRP composite after exposure to freeze-thaw cycle, it might be due to the degradation of exposed concrete itself [9-11]. It was also reported that weathering effect and environmental exposure such as alternating wetting and drying cycles, temperature changes, salt water exposure and exposure to ultraviolet radiation may lead to the deterioration of FRP composite [12].

As a part of an on-going research program on structural integrity evaluation of RC columns retrofitted with FRP wraps, a project was carried out with the primary objective to investigate the effect of combined environmental cycles on RC column wrapped with CFRP and GFRP, which consists of repeated cycles of freeze-thaw, high-temperature and ultraviolet radiation, and high-humidity. Particular focus was on the evaluation of strength and ductility of the FRP strengthened column after combined environmental conditioning though compression tests.

2. EXPERIMENTAL PROGRAM

2.1 Test Matrix

The test columns are divided mainly into two groups: small-scale RC columns and full-scale RC columns. The experimental parameters include type of FRP sheets and environmental conditioning. As shown in Table [1], a total of 30 small-scale columns are included in this study. Column S-C0-CONT is used as the control specimen, which represents the unwrapped RC column. The other columns were strengthened with two different types of FRP sheet (CFRP and GFRP) and then conditioned under five different environmental cycles: (1) room temperature, (2) freeze-thaw cycles, (3) freeze-thaw cycles and exposure to saline solution, (4) combined environmental cycles (as shown in Fig. [2]), and (5) combined environmental cycles and saline solution. In addition, a total of 6 full-scale columns were tested under similar conditions: (1) room temperature, (2) freeze-thaw cycles, and (3) combined environmental cycles. As listed in Table [1], column identification consists of column size, FRP sheet type and environmental conditioning type: S and F for small-scale and full-scale, respectively; C and G for CFRP and GFRP sheet, respectively; CONT, F/Th and CE for control, freeze-thaw, and combined environmental cycles, respectively. The symbol Na in the column nomenclature refers to columns soaked in saline solution during the environmental conditioning.

Table [1]: Test matrix

Specimen		FRP layer	FRP type	Description of environmental conditioning	Number of specimens
Small-Scale Column	S-C0-CONT	0		Control, room temperature	3
	S-C-CONT	1	CFRP	Control, room temperature	3
	S-G-CONT	1	GFRP	Control, room temperature	3
	S-C-F/Th	1	CFRP	Freeze-thaw cycle	3
	S-C-CE	1	CFRP	Combined environmental cycle	3
	S-G-F/Th	1	GFRP	Freeze-thaw cycle	3
	S-G-CE	1	GFRP	Combined environmental cycle	3
	S-C-Na-F/Th	1	CFRP	Freeze-thaw cycle and saline solution	3
	S-G-Na-F/Th	1	GFRP	Freeze-thaw cycle and saline solution	3
	S-C-Na-CE	1	CFRP	Combined environmental cycle and saline solution	3
	Total				30
Full-Scale Column	F-C-CONT	1	CFRP	Control, room temperature	1
	F-G-CONT	1	GFRP	Control, room temperature	1
	F-C-F/Th	1	CFRP	Freeze-thaw cycle	1
	F-G-F/Th	1	GFRP	Freeze-thaw cycle	1
	F-C-CE	1	CFRP	Combined environmental cycle	1
	F-G-CE	1	GFRP	Combined environmental cycle	1
	Total				6

2.2 Materials

2.2.1 Concrete

The concrete used for small-scale columns was produced in the laboratory according to the mixture proportion shown in Table [2]. The average compressive strength of the concrete was determined to be 12.24 MPa based on the compression test result of six standard cylinders (152 x 304 mm). Since most of RC structures to be repaired were constructed more than approximately 10 to 20 years ago, the concrete mix design in this study was adapted from the typical mix design with 28 day strength of 24 MPa in bridge construction 20 years ago. However, the resulting strength was very low because of use of different aggregate and additives. The slump and air content were 200 mm and 10 %, respectively. The low compressive strength of the concrete may be due to the high air content in the concrete. All columns were produced of same concrete strength.

The full-scale columns were made of ready-mixed concrete. The average compressive strength of the concrete was determined to be 28.3 MPa based on the compression test result of three standard cylinders.

Table [2]: Mixture proportion of the concrete (unit: kg/m^3)

W/C	Cement	Water	Coarse aggregate	Fine aggregate	Air Entraining agent (ml)
0.62	291	180	756	1,081	150

2.2.2 Reinforcement

No. 3 reinforcing bars (nominal diameter of 9.5 mm) of 400 MPa yield strength was used for longitudinal reinforcement for both small-scale and full-scale columns. Steel wire with diameter of 3.2 mm was used for the spiral reinforcement of small-scale columns while No. 2 reinforcing bar (nominal diameter of 6.4 mm) was used for the spiral reinforcement of full-scale columns.

2.2.3 FRP sheet

Two types of FRP sheets, namely Mbrace™ CF High Tensile Carbon Fiber and Mbrace™ EG900 E-Glass Fiber, were used to wrap and strengthen the columns [13]. The mechanical properties of the FRP are shown in Table [3]. The epoxy-based resin, namely Mbrace™ primer and saturant were used for the first coating and for impregnating the dry fibers. The FRP sheets were applied using the wet lay-up technique: First, a coat of primer was applied to ensure a good bond between the sheets and concrete surface and a saturant was used to saturate the fibers and bond them to the concrete surface.

Table [3]: Mechanical properties of FRP sheets

Fiber Type	Thickness (mm)	Design strength (MPa)	Design strain (mm/mm)	Young's Modulus (GPa)
Carbon (CFRP)	0.16	3,790	0.017	227
Glass (GFRP)	0.35	1,520	0.021	72.4

2.3 Specimen detail and test setup

2.3.1 Small-scale columns

The diameter of the small-scale columns was 152 mm and the height was 457 mm. Three deformed reinforcing bars with a nominal diameter of 9.5 mm were used for longitudinal reinforcement (reinforcement ratio ρ was selected to be around 0.012) while steel wire with the diameter of 3.2 mm was used for the spiral reinforcement. The spacing of the spiral reinforcement was 25.4 mm. The schematic of the small-scale column details and test setup are presented in Fig. [1]-(a).

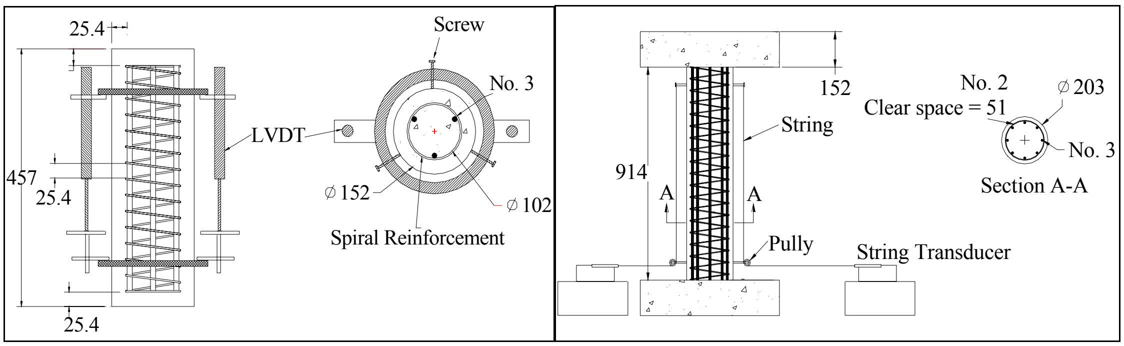
All the specimens were tested under uni-axial compression. The load was applied using hydraulic universal testing machine at a constant loading rate of approximately 0.2 MPa/sec. Two Linear variable differential transducers (LVDT) were used to measure the longitudinal deformation. The gage length of the LVDT was approximately 305 mm covering two-thirds of the length of the column. To monitor the radial strain of the specimen, strain gages were attached to the surface of the FRP sheet at the mid-height of the specimen.

FRP sheets were applied using wet-lay up technique along the height of the column. The fibers were oriented at 90 degree relative to the primary vertical axis of the column. Additional CFRP sheet strips having a width of 51 mm were applied to the top and bottom end of the column to provide additional confinement and to avoid the column edge failure. Sulfa capping was applied on the top and bottom surfaces prior to testing.

2.3.2 Full-scale columns

As shown in Fig. [1]-(b), full-scale column consisted of circular cross-section in the middle test region and larger square concrete block at both ends. The concrete blocks were included to avoid failure at end of column and simulate the case of existing foundation or bridge cap. The diameter of the cross-section was 203 mm with a column length of 914 mm.

Longitudinal reinforcement was made of No. 3 reinforcing rebar (nominal diameter of 9.5 mm) of 400 MPa yield strength and transverse reinforcement was made of steel wire with the diameter of 6.4 mm. The spacing of the spiral reinforcement was 51 mm. String transducers were used to measure the longitudinal deformation. Having a gage length of 762 mm. To monitor the radial strain of the column, strain gages were also attached to the surface of the FRP sheet at the mid-height of the column.



(a) Small-scale column **(b) Full-scale column**

Fig. [1]: Details of test-columns and test setup (unit: mm)

2.4 Combined environmental cycles

The combined environmental cycles shown in Fig. [2] describes the equivalent of a one-year cycle, which consists of four different temperature ranges representing the seasonal changes. The described environmental cycles are apparently more severe than the average temperature in North America and the tests are designed to simulate a more severe situation. The combined environmental cycles were repeated 10 times in order to simulate 10 years of out door exposure. However, it should be noted that accelerated shorter cycles usually cause more severe result, thus it could be assumed that this combined environmental cycles simulate a larger period than the 10 years.

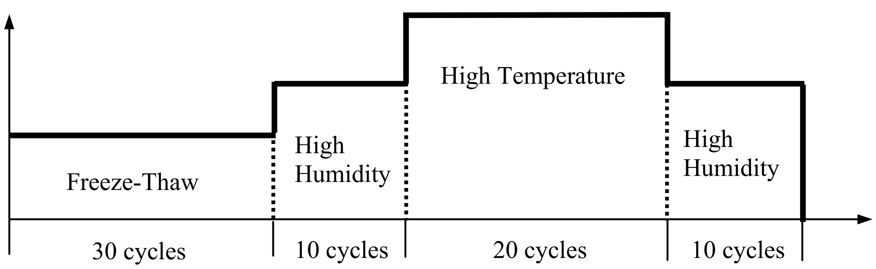


Fig. [2]: Combined environmental cycles

In Fig. [2], the freeze-thaw cycles consisted of one-hour freeze at -18°C, one-hour thaw at 10°C, and 30 min. ramping up and down. The high temperature cycles consisted of one-hour low temperature of 27°C, one-hour high temperature of 50°C, and 20 min. ramping up and down. Ultraviolet radiation was applied during the high temperature cycles. The ultraviolet lamps positioned in the environmental chamber exposed the columns to an irradiance of 6.80 x 10^{-2} W/cm^2 in a spectral band of 300-800 nm. The high humidity cycle consisted of 20-min. 60 % R.H. at 16°C, 20-min. 100 % R.H. at 27°C, and 30 min. ramping up and down.

3. TEST RESULTS AND DISCUSSIONS

All columns were tested in concentric compression and the generated stress-strain relationships are shown in Figs. [3] through [8]. The ultimate strength and deformations of all columns are presented in Table [4]. This table includes also the respective comparison of the environmentally conditioned columns in terms of ratios of the ultimate strength and deformation of all tested columns to those of their control columns.

3.1 Ultimate strength

As shown in Table [4], the ultimate strength of the small-scale columns wrapped with CFRP sheet was decreased slightly due to the freeze-thaw cycles. The ultimate strength of the control column S-C-CONT is 40.5 MPa while that of column S-C-F/Th is 38.1 MPa, which is just 6 % less than that of that of control specimen S-C-CONT. For the GFRP wrapped small-scale column, the decrease in ultimate strength due to the freeze-thaw cycle is minimal. The ultimate strength is 40.1 MPa and 39.6 MPa for control column S-G-CONT and column S-G-F/Th, respectively.

The effect of the application of the saline solution during the freeze-thaw cycles on the columns wrapped with CFRP is not significant based on the comparison between column S-C-F/Th and S-C-Na-F/TH. The ultimate strength of column S-C-Na-F/Th is 37.7 MPa, which is very close to that of the column S-C-F/Th. The decrease in ultimate strength of GFRP wrapped column due to the saline solution is noticed from the comparison between column S-G-F/Th and S-G-Na-F/Th. The ultimate strength of the column S-G-Na-F/Th is 37.9 MPa, which is 95 % of that of the column S-G-CONT.

Table [4]: Summary of test results

Specimen		Ultimate strength		Ultimate axial strain		Ultimate radial strain	
		f'_c (MPa)	**f'_c / $f'_{c,CONT}$**	**$\varepsilon_{u,a}$($x10^{-6}$)**	**$\varepsilon_{u,a}$ /$\varepsilon_{u,a,CONT}$**	**$\varepsilon_{u,r}$($x10^{-6}$)**	**$\varepsilon_{u,r}$ /$\varepsilon_{u,r,CONT}$**
Small-Scale Columns	S-C0-CONT	15.7	1.0	29416	1.0	622	1.0
	S-C-CONT	40.5	1.0	34617	1.0	15320	1.0
	S-C-F/Th	38.1	0.94	25042	0.72	5258	0.34
	S-C-Na-F/Th	37.7	0.93	26500	0.77	7220	0.47
	S-C-CE	36.9	0.91	26125	0.76	9435	0.62
	S-C-Na-CE	36.7	0.91	25208	0.73	7999	0.52
	S-G-CONT	40.0	1.0	36292	1.0	13576	1.0
	S-G-F/Th	39.6	0.99	29458	0.81	13010	0.96
	S-G-Na-F/Th	37.9	0.95	25750	0.71	11010	0.81
	S-G-CE	40.9	1.02	39500	1.09	14159	1.04
Full- Scale Columns	F-C-CONT	47.7	1.0	8650	1.0	6788	1.0
	F-C-F/Th	47.7	1.0	9633	1.13	6869	1.01
	F-C-CE	47.9	1.0	11250	1.30	6434	0.96
	F-G-CONT	50.1	1.0	13533	1.0	9941	1.0
	F-G-F/Th	49.7	0.99	13950	1.03	12390	1.24
	F-G-CE	45.3	0.90	10683	0.79	7671	0.77

The effect of combined environmental cycles on the degradation of ultimate strength of small-scale column wrapped with CFRP sheet is more evident than that of freeze-thaw cycle (comparing columns S-C-CE and S-C-F/Th.). The ultimate strength of column S-C-CE is

36.9 MPa, which is 91 % of that of control column S-C-CONT, while the ultimate strength of column S-C-F/Th is 38.1 MPa, which is 94 % of that of control column S-C-CONT. However, this trend is not observed for small-scale columns wrapped with GFRP sheets if comparing S-G-CE and S-G-F/Th. The ultimate strength of column S-G-CE is slightly higher than that of column S-G-F/Th and that of control column S-G-CONT. This could be attributed to the fact that concrete strength of column S-G-CE is higher than that of column S-G-CONT and S-G-F/Th. In order to study the effect of the saline solution, during the combined environmental cycles, column S-C-Na-CE was soaked in a 5 % NaCl solution. The results show no effect of saline solution, that is the ultimate strength of column S-C-Na-CE is 36.8 MPa, which is almost the same of that of column S-C-CE.

For the case of full-scale columns, the change in ultimate strength due to both freeze-thaw cycles and the combined environmental cycles is not significant except for the case of column F-G-CE. Considering the difference between the compressive strength of concrete used for small-scale columns and that of concrete used for full-scale columns, small-scale columns would be more susceptible to freeze-thaw and the combined environmental cycles due to low quality of the concrete itself. Furthermore, none of the concrete in the test region of the full-scale columns was directly exposed to freeze and thaw due to the existing larger concrete blocks at the ends of the column and FRP sheet were wrapped all around the test region. As for small-scale columns, concrete was directly exposed to freeze and thaw at both ends of columns. Thus it could be hypothesized that in the case of small-scale columns if concrete itself showed no degradation, the FRP strengthened system would not be affected by the freeze-thaw and/or combined environmental cycles, and the ultimate strength of the system would not decrease.

3.2 Ductility

The axial stress-strain relationship of small-scale column wrapped with CFRP sheet is presented in Fig. [3]. In this figure, it is shown that the ultimate axial strain is decreased due to the freeze-thaw and combined environmental cycles. The ultimate strains of column S-C-F/Th and S-C-Na-CE are just 72 % and 73 %, respectively, as compared to the strain of the control column S-C-CONT. The effect of the saline solution on the change of ultimate strain is not observed.

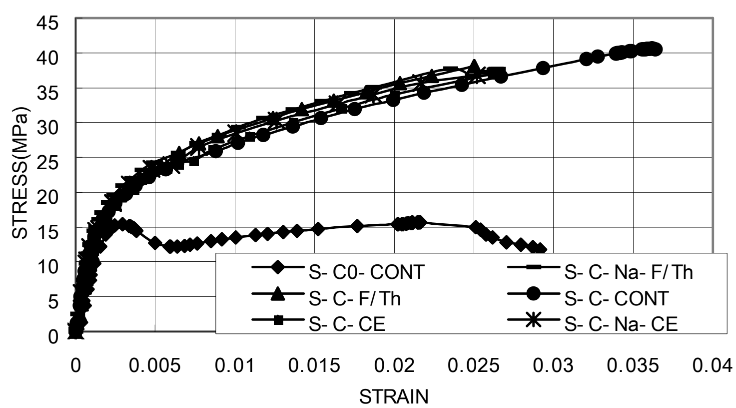


Fig. [3]: Axial Stress-strain curves of small-scale columns wrapped with CFRP sheet

The radial stress-strain relationships of small-scale columns wrapped with CFRP sheet are presented in Fig. [4]. The decrease in radial ultimate strain of small-scale column wrapped with CFRP sheet due to the freeze-thaw and combined environmental cycles is somewhat very significant. The axial stress-strain relationship of the small-scale columns wrapped with GFRP sheet is presented in Fig. [5]. The ultimate axial strain shows reduction due to freeze-thaw cycle and the presence of saline shows additional reduction. From Table [4], the ultimate strain of column S-G-CONT, S-G-F/Th and S-G-Na-F/Th are 36,292 x 10^{-6}, 29,458 x$10^{-6}$and 25,750x10^{-6}, respectively.

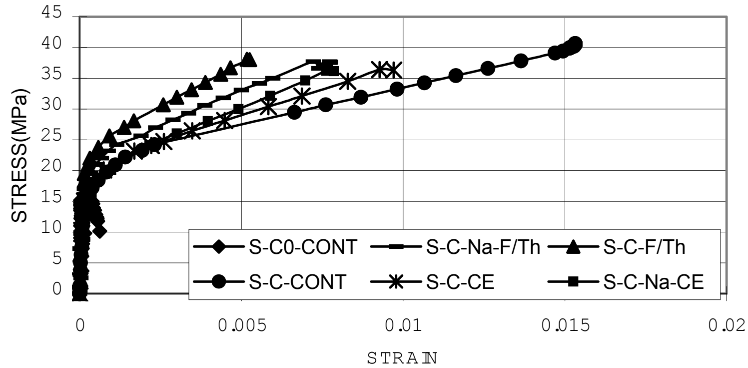


Fig. [4]: Radial stress-strain curves of small-scale columns wrapped with CFRP sheet

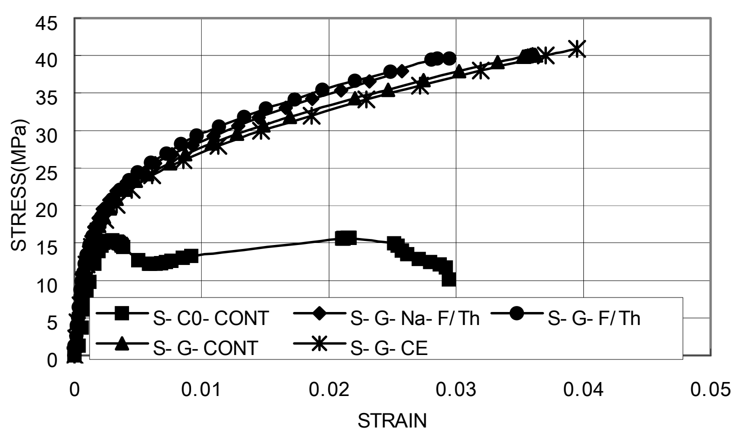


Fig. [5]: Axial stress-strain curves of small-scale columns wrapped with GFRP sheet

The radial stress-strain relationships of small-scale columns wrapped with GFRP sheet is presented in Fig. [6]. Like the change of the axial strain, the ultimate radial strain was slightly decreased due to the freeze-thaw and/or saline solution. From Table [4], the ultimate radial strain of column S-G-CONT, S-G-F/Th and S-G-Na-F/Th are 13,576 x 10^{-6}, 13,010 x $10^{-6}$and 11,010 x 10^{-6}, respectively.

The stress-strain relationships of the full-scale columns wrapped with CFRP sheet is presented in Fig [7]. The figure shows that neither the ultimate axial strain nor the radial strain were affected by freeze-thaw and/or combined environmental cycles. Fig. [8] shows the stress-strain relationships of the full-scale columns wrapped with GFRP sheets. Similarly, this figure shows no significant change in the ultimate axial strain due to exposure to the freeze-thaw cycles. However, slight increase in ultimate radial strain was observed due to the freeze-thaw cycles, which could be attributed to variability in test measurement. As for column F-G-CE, all the values are significantly smaller than those of all the other GFRP strengthened full-scale columns, which may be explained by the failure resulting from the slight eccentricity of applied compression load. Thus, the failure occurred in the test region at a slightly lower applied load than expected.

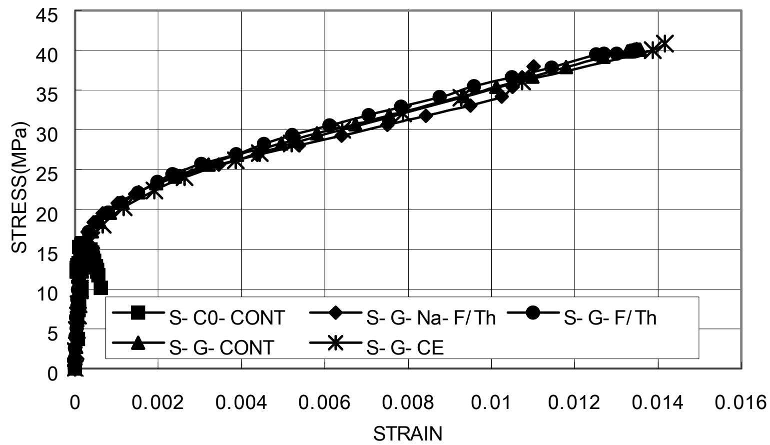


Fig. [6]: Radial stress-strain curves of small-scale columns wrapped with GFRP Sheet

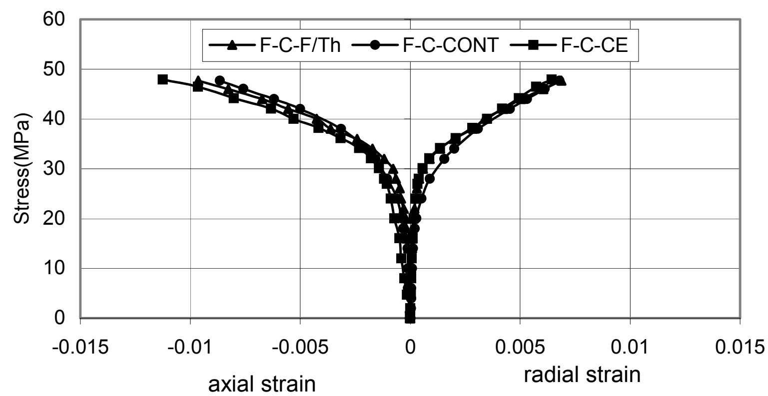


Fig. [7]: Stress-strain curves of full-scale columns wrapped with CFRP sheet

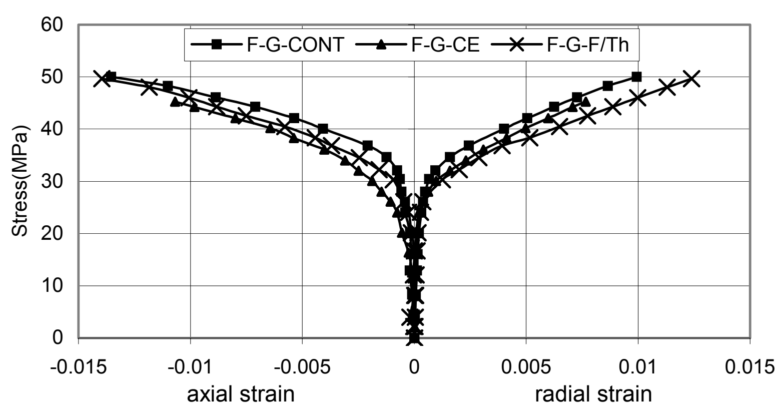


Fig. [8]: Stress-strain curves of full-scale columns wrapped with GFRP sheet

Overall, it was found that there is no significant difference between the effects of freeze-thaw cycles and the effects of combined environmental cycles on the degradation of RC columns wrapped with FRP sheets.

4. CONCLUSIONS

Based on the results of this study, the following conclusions can be drawn:

1. The decrease in ultimate strength due to freeze-thaw cycles and combined environmental cycles used in this test sequence was not significant and the slight noticed degradation in small-scale columns could be attributed in large part to the degradation of concrete itself due to the freeze-thaw cycle rather than FRP sheets.
2. The decrease in ultimate axial strain of both CFRP and GFRP wrapped small-scale columns due to the freeze-thaw and combined environmental cycles was considerable.
3. The decrease in ultimate radial strain of the small-scale columns wrapped with CFRP sheets was significant while that of the small-scale columns wrapped with GFRP sheets was not very significant.
4. GFRP wrapped RC column was affected by the saline solution more than CFRP wrapped RC column.

If the results of this study can be confirmed to say that there is no significant difference between the effects of freeze-thaw cycles and the effects of combined environmental cycles, then it could be generalized to state that a combination of high temperature cycles, high humidity cycles and ultraviolet radiation may not affect the performance of RC structures wrapped with FRP sheet.

5. ACKNOWLEGEMENT

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