CONFINEMENT OF AAR EXPANSION IN CYLINDRICAL REINFORCED COLUMNS BY CFRP WRAPPING

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Abstract

Bridge columns and beams are amongst the elements affected by alkali-aggregate reaction (AAR). A potential repair is wrapping of affected element by epoxy-bonded carbon fibre reinforced polymer (CFRP). A previous investigation by the authors on CFRP-wrapping of AAR-affected square columns showed that the wrapping reduced the expansion rate, but did not stop it. This was attributed to (a): Square shape of columns, not providing full confinement on the sides of columns, and (b): Application of only one layer of normal-modulus (240GPa) CFRP, rather than multiple layers of higher modulus (640 GPa) CFRP.

The present investigation employed circular-section columns and multiple layers of CFRP (240 and 640 GPa). Expansion was measured in vertical and horizontal directions in concrete, on reinforcement bars and on CFRP. the effects of column shape, CFRP modulus and number of layers on the confinement of AAR expansion are discussed in relation to the repair of AAR-affected columns.

Keywords: AAR, DEF, Expansion, "CFRP-wrapping", "Concrete-jacketing"

1 INTRODUCTION

Alkali-aggregate reaction (AAR) in concrete is an expansive process and eventually leads to cracking of concrete, and losses in the mechanical properties of the affected concrete. Repair of the AAR-affected concrete elements is complicated by the ongoing expansion process, which can proceed at varying rates and to different extents (residual expansion), depending on the reactivity of the aggregate, concrete alkali content, moisture availability, etc. Repair would be more effective when the reaction is largely dissipated and the residual expansion is small.

Traditional crack repair techniques for damaged elements subjected to significant on-going expansion could be a waste of money, as cracks would reappear. Relatively modern and reliable technology is available, using externally bonded carbon fibre reinforced polymer (CFRP) wrapping, for retrofitting concrete elements damaged by mechanical actions such as earthquake, and design guides have been developed for this type of application [1]. A recent study [2] revealed that CFRP wrapping significantly improved the load carrying capacity and ductility of the RC columns damaged by AAR, in comparison with the untreated columns.

The effectiveness of this type of repair systems has not been adequately demonstrated for controlling expansion of concrete elements with ongoing expansion. Wrapping small, AAR-affected concrete cylinders with CFRP [3] was partially effective in reducing the expansion, but did not eliminate it. Using columns of 300x300 mm in cross section [4], it found that wrapping columns with one layer of CFRP (240 GPa modulus) was not sufficient to reduce the AAR expansion to acceptable levels. The column corners were chamfered to 40 mm radius, as previous studies [5] had shown that the corner radius significantly affected the confinement stress in rectangular sections. The lack of effective confinement was attributed to the square shape of the columns [6], which prevented uniform confinement over the whole periphery of square columns, but only at the corners. Analysis showed that the confinement efficiency of CFRP wrapping was 0.36 for the square section columns, compared to a value of 1.0 for circular columns of 300 mm diameter. Other researchers [7] found that the maximum calculated confinement pressure for their square columns, wrapped with 1 and 2 layers of CFRP, was 3.8MPa and 7.6 MPa, respectively, whereas for equivalent circular columns the corresponding confining pressures were 4.57MPa and 9.33 MPa, respectively. The increase in the confining pressure means that the tensile strain of the fibre is also increased. In the square columns the confinement is concentrated at the corners, whereas in circular columns it is uniformly distributed over the circumference.

The present paper provides data on the efficiency of different number of layers of two types of CFRP of different moduli in reducing the AAR-expansion in circular-section columns to complement data provided earlier on square-section columns.

2 EXPERIMENTAL WORK

2.1 Concrete materials

The coarse aggregate used was a reactive rhyodacite (nominal size 20 mm and 14 mm) and the fine aggregates non-reactive sand. The cement was the Blue Circle General Purpose Cement. The cement alkali content was adjusted to 1.50% by mass of cement by adding sodium hydroxide in the mixing water. Rheobuild 1000 High Range Water Reducer was used to control the slump.

The concrete mix contained 450 kg/m^3 cement, 1100 kg/m^3 coarse aggregate, 690 kg/m^3 sand and 189 kg/m^3 water (water to cement ratio of 0.42). The water reducer was used at the rate of 3.2 kg/m3 (0.6 L/100 kg cement). The workability of mix was very high, and slump test resulted in collapse.

This mix proportion was used to manufacturel 10 columns. To test the compressive strength, three standard cylinders for Mix 2 and four cylinders for Mix 10 were made. The cylinders with mould were wrapped and cured at 38°C after initial setting until 24 hours (the same as for columns). The concrete cylinders were then stored in a fog room at 23°C until testing at the age of 28 days.

2.2 Design of columns

Configuration of columns

Ten reinforced concrete columns, 300 mm in diameter and 1100 mm high, were fabricated, incorporating eight evenly distributed vertical steel bars (12 mm diameter) and four ligature bars (10 mm diameter). The ligature bars were placed at the top, 2/3 of height, 1/3 of height and bottom (Figure 1). Concrete cover thickness was at least 40 mm. The reinforcement ratio was 0.0127 (or 1.27%), with total steel volume / column volume = 0.0157 (or 1.57%). The lateral and vertical bars were welded at their contact points.

To accelerate the hydration at early age, each column was covered with a thick plastic sheet on the top and moved into a constant temperature room maintained at 38°C (at age of about 3 hours). It was expected that hydration heat would be high for this concrete mix (450 kg/m^3 cement) and effectively increase the temperature of the concrete and accelerate the strength development. This condition was assumed to be able to raise the concrete temperature over 60-70°C and could result in some delayed ettringite formation which would further enhance the expansion.

CFRP Materials

Two types of CFRP sheets, both 300 mm wide, were used for the wrapping of columns; being of 240 GPa and 640 GPa moduli. The technical specification of the fibres and the main adhesive are given in Table 1.

Wrapping of columns

The columns were scheduled to be used for wrapping with CFRP as shown in Table 2. The wrapping was performed professionally by a repair company engaged in CFRP installation, after smoothing and cleaning the concrete surface. The actual height of the columns was about 1080 mm, and the width of CFRP sheets 300mm, requiring four rounds of CFRP sheets to cover the column, each round overlapping the round glued earlier. This practice, in effect, made double layered bands and extra layer at the end of each sheet.

2.3 Curing Conditions

Each column was moved out of the 38°C room and the mould (the plastic pipe) was stripped off at age of 1 day. The column was then wrapped in plastic bags with some water and stored in the casting room until the concrete was sufficiently matured; water being added from the top of columns to continue hydration during this period. The first two to three months of the age of columns coincided with summer period, and the storage temperature was above 20°C. Each column was subsequently placed in a container half-filled with water (to half height of columns). The whole assembly was covered by a large plastic bag and moved into a condition room maintained at 38°C. Columns 1 - 6, which were planned for wrapping at the age of one year, were moved into the 38°C room in February 2009.

Columns 7-10 were wrapped with CFRP, as detailed in Table 2, at the age of about 2 months. These columns were still kept in the same casting room to allow the hardening of the epoxy adhesive and attaching strain gauges on the surface of the CFRP wrapping. The columns were also placed in containers filled with water to half-height, the assembly being wrapped in plastic bags and moved into the 38°C room at the age of about five months.

2.4 Strain Gauges

Strain gauges in concrete were placed in alignment with the centre-line, at middle height of both upper and lower half of the column. Strain gauges were attached on the outer surfaces of steel bars either by welding or using adhesives, following manufacturers' instructions. For the columns wrapped with CFRP, strain gauges were glued on the surface of the wrapping. Figure 1 shows a schematic presentation of columns and the locations of the strain gauges, similar to those used in the previous study on square columns [4].

The concrete embedded gauges (CE) were named based on their location and orientation, as follows:

- CET V: Top part (upper half) of column; vertically placed in the centre.
- CET H: Top part (upper half) of column; horizontally placed above middle ligature bar
- CEB V: Bottom part (lower half) of column; vertically placed in the centre.
- CEB H: Bottom part (lower half) of column; horizontally placed below middle ligature bar

Strain gauges on vertical bars were fixed at three heights, i.e. top (2/3 of cage height), middle (1/2 of the cage height) and bottom (1/3 of cage height). Two types of gauges were used; either welded or glued on steel bars. Based on the location and fixing type, strain gauges on vertical bars were designated to signify bar number (c.f. Figure 1); location (T, M, B for Top, Middle and Bottom); type (W, S for weldable or surface glued). For example designation 1TW indicates: Bar No.1, Top part of reinforcement cage, and weldable gauge.

Strain gauges on the ligature bars were fixed at the middle-to-top (2/3 of cage height), middle-to-bottom (1/3 of the cage height) and bottom bar. Two types of gauges were used, i.e. welded or glued on steel bars. Based on the location and fixing type, strain gauges on ligature bars were given designations to signify location (MT, MB, B for Middle-to-Top, Middle-to-Bottom and Bottom, respectively); vertical bar numbers (c.f. Figure 1); type (W, S for weldable and surface-glued, respectively. For example, MT34W indicate: Middle-to-Top ligature, between vertical bars No.3 and No4, weldable gauge, etc.

Strain gauges on CFRP wrapping were horizontally fixed on the upper part (0.16 - 0.30m from top of columns) and lower part of column (0.63 - 0.90m from top), and named according to their locations.

3 RESULTS AND DISCUSSION

3.1 Concrete Strength

The compressive strength of concrete was 18.8 MPa at 1 day, and 33.9±0.7MPa at 28 days, which was lower than expected for cement content of 450 kg/m^3, i.e. 50MPa. This was due to the added alkali in the mixes [8]. However, the 1-day strength was relatively high due to the 38°C during in the first day.

3.2 Expansion measurement

Strain gauges installed in each column register the linear length change of concrete in the direction of the strain gauge, vertical steel bars and horizontal tie bars (ligature). For the CFRP-wrapped columns, two gauges were horizontally fixed on the outer surface of CFRP, after hardening and stabilisation of the wrapping adhesive, for measuring the circumferential length changes on the periphery of cylindrical columns, the values of which are expected to be larger (by a factor of π) than the linear expansion of concrete.

The average expansion of each type of gauge was calculated and plotted against time. The average expansion of main steel bars, ligature bars and CFRP (if applicable) was also plotted against the average expansion of concrete. Due to the large amount of data collected, only a summary of these results is presented in this paper.

3.3 Expansion of Concrete

Columns without wrapping and columns wrapped with CFRP at early age

Figure 2 presents the expansion results for Columns without CFRP wrapping (Column1 and Columns 2 – 6, up to about 520 days, i.e., before wrapping) in comparison with those for columns which were wrapped at early age (Columns 7-10). The results demonstrate that concrete expansion, as measured by the concrete embedded gauges, was greater in the lower, submerged part of the columns than in the drier, upper part. This is attributed to the better availability of moisture in the lower part. There was no significant difference between the expansion values measured by the vertically and horizontally placed gauges; i.e., expansion along the length of columns was similar to that across the width of columns.

Figure 2 also includes the average expansion values measured by the two sensors embedded in each part of columns, and show that the six columns before wrapping exhibited varying expansion levels, especially for the lower part of columns. The average expansion rates were 1.90μm/m per day for the upper part, and 2.4 μm /m per day, for the lower part of columns.

The results for Columns 7 – 10, which were wrapped with CFRP before being moved into humid conditions at 38°C, are also given in Figure 2. They had shown about 100μm/m expansion before being wrapped with CFRP, and an average expansion of 510μm/m at the age of 470 days. Unlike the columns without wrapping, there was no significant difference in expansion rate between the upper part (0.96μm/m per day) and the lower part (0.89μm/m per day) of the wrapped columns, which is due to more uniform moisture distribution in the lower and upper parts of these columns, because the CFRP wrapping prevented drying of concrete. The average expansion rate of all the four early age wrapped columns was 0.92μm/m per day.

There was no significant difference in expansion between Columns 7- 9, which were wrapped with 3, 2 and 1 layers of 240GPa CFRP, respectively. However, Column 10, which was wrapped with 640GPa CFRP, showed the smallest expansion. Compared with the columns without wrapping, the wrapped columns showed consistently lower expansion (Figure 2), which is due to the confinement provided by the wrapping.

These results are similar to those obtained for square columns(6), in the sense that the CFRP wrapping reduced the expansion rate but did not eliminate it or reduce to safe levels.

Columns wrapped with CFRP at later age

Columns 2, 3, 4, 5 and 6 were wrapped at ages between 513-540 days, using different numbers of layers of CFRP (Table 2). They had expanded about 1000 μm/m before the wrapping, which had resulted in 0.33 mm wide cracks. Figure 3 presents the concrete expansion data obtained before and after wrapping of Columns 2-6, which show that:

1. The effect of wrapping with multiple layers of CFRP on concrete expansion cannot clearly be quantified as also seen in Figures 4 and 5. The effect of multiple layers appears to be similar to that of a single layer on confinement of expansion. This is partly due to the scatter observed in the expansion (Figures 2 and 3). Another possible reason may be that the confining effect of multiple layers of CFRP is probably controlled by the volume and properties of epoxy resin present in the wrapping, rather than by the number of layers of CFRP. Particularly, the creep of epoxy resin at the temperature of 38 °C and possible slipping of CFRP layers, due to concrete expansion forces, may be important.
2. The high modulus CFRP (640 GPa) showed a better confining effect compared to the normal modulus CFRP (240 GPa). For both types of CFRP, 2-layer wrapping resulted in an improved confinement than the 1-layer counterparts; but the effect was not proportional to their relative stiffness. Note that the two-layer high modulus wrapping was coincidentally applied on a column which already had the lowest expansion (Column 6).
3. Since the wrapping at later ages of Columns 2-6, the columns wrapped at early age (Columns 7-10) have developed larger expansion than those wrapped at later ages. This arose because more of the AAR potential was exhausted by the time of wrapping (i.e., lower residual expansion for columns which were wrapped at later ages). The continual expansion demonstrated by the columns wrapped at early age may suggest that some relaxation is occurring in the CFRP with time.

Other studies [7], using very reactive fused silica as reactive aggregate, also found that columns which were wrapped at the age of one month (expansive phase) had higher deformation in comparison with those wrapped after two months (when the reaction had plateaued). This was also attributed to the difference in the residual expansion of the columns concerned, being higher for columns wrapped earlier.

3.4 Length Change of Vertical Bars

Many of the gauges glued to the steel surface failed within one year, and the readings rapidly decreased and became negative.These erroneous results are not used in the analysis. Figure 6 shows the length changes of vertical bars, plotted against concrete expansion for the upper parts of columns without CFRP wrapping. Strain development in the vertical bars started when the concrete expansion was about 200μm/m, and continued at the same rate as the concrete. The ratio of steel strain to concrete expansion was 1.06 (Figure 6). The ratio was 0.82 for the lower part s of columns, i.e., concrete expanded at a higher rate due to better moisture availability.

Similar patterns were obtained for columns wrapped with CFRP. After wrapping of Columns 2-6, at about 530 days, the strain of vertical steel bars still increased in proportion to that of concrete, but the ratio was reduced by 10%. In the columns wrapped with CFRP at early age, the main steel bars started to show positive strains when concrete strain was about 300 - 400μm/m. The proportionality of steel strain to concrete expansion was poor. Nevertheless, the ratio of strain of steel to concrete expansion was 0.6 for both the upper and the lower parts of columns, which is lower compared with the columns without wrapping.

It is noted that negative strains developed in the vertical steel bars at early ages. This may have arisen due to the fact that the column temperature must have risen substantially because of cement hydration during the initial curing at 38°C, causing thermal expansion of the steel bars. In subsequent cooling down, the steel bars would have developed the thermal contractions which were recorded at early ages.

Analysis of strain

The strain in the vertical bars is mainly caused by the concrete expansion in the longitudinal direction, and enhanced by the pressure from lateral directions. Given the areas of steel and concrete (A_{steel} and A_{conc}), the stress in the steel (σ_{steel}) can be calculated in order to assess the expansion pressure in the concrete (p_{conc}), as follows:

$$p_{conc}A_{conc} = \sigma_{steel}A_{steel} \text{ ; or } p_{conc} = \frac{A_{steel}}{A_{conc}} \frac{\varepsilon}{1+2\nu} E_{steel},$$

Where E_{steel} =200GPa and Poisson Ratio ν = 0.3 for mild steel. The area ratio of vertical steel to concrete of the columns (A_{steel} / A_{conc}) was 0.0129 for the columns. The average strain of main steel bars of columns 1 to 6, at 530 days, was 940μm/m. The above values yield a concrete pressure of 1.5Mpa, which is the magnitude of stress produced by the AAR expansion in the concrete.

3.5 Length Change of Ligature Bars

Most of the gauges glued on ligature bars gave extremely large negative strains after several months, which is taken to indicate gauge failure. However, most welded gauges showed consistent positive, but small strains. Similar to the strains measured on the vertical bars, the strains on ligature bars lagged behind the expansion of concrete, probably due to the initial thermal expansion of steel, resulting from high temperature in concrete during hardening, and subsequent contraction due to cooling. Moreover, as the ligature bars were welded to the vertical bars, the stiffness (against bending) of vertical bars may also have helped the ligature bars resist the expansion pressure exerted from concrete, leading to small strains in the bars. Overall, no significant strain developed in the ligature bars (varying between -400 and +200 μm/m) , in contrast to the large strains developed in vertical bars. Small, positive strains were noted in the ligature bars of Columns 3, 5, 9 and 10 with increasing expansion of concrete.

3.6 Length change of CFRP wrapping

The strain measured on the CFRP wrapping for Columns 7-10 (which were wrapped at early age) increased with the increase in concrete expansion, when the latter exceeded about 200μm/m (Figure 7). The circumferential strain of the CFRP was about 1.5 times that of linear concrete expansion during the same period. The strain developed in the 640 GPa CFRP wrap was clearly lower than those of 240GPa CFRP wrap.

The number of layers of the latter did not influence the magnitude of the CFRP strain. Other research employing circular columns (7) found that the deformation of two layers of CFRP wrap was higher than the deformation of one layer. The authors interpreted their results to mean that the confinement provided by two layers of CFRP was more pronounced.

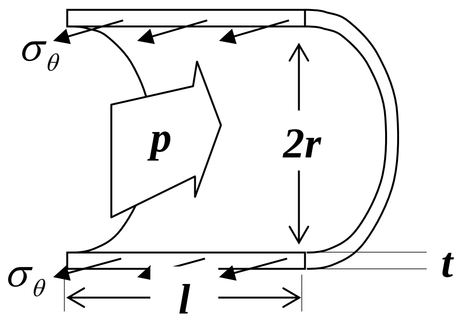
The pattern of circumferential strain development in the CFRP wrapping for Columns 2-6 (which were wrapped at later ages) was different. The CFRP strain increased 2 - 3 times that of concrete, irrespective of type and number of CFRP layers. The number of layers did not seem to have a significant influence on the expansion, the same as for the columns wrapped at early age.

3.7 Confinement

In the present work, confinement of concrete expansion was effected by the steel cage and the CFRP wrapping. It has been reported that a reinforcement ratio of 1% can reduce the expansion by 30-50% of the free expansion [9]. The steel cage confines the core of the column whereas the wrapping confines the whole column, including the cover concrete. The external confinement changes the stresses exerted on the steel bars, i.e. it reduces the circumferential (tensile) stress, and increases the radial stress (compression).

In compression tests conducted by other researchers [10], CFRP was found to take most of the stress in wrapped columns whether with or without ligature steel. In the absence of external wrapping, the AAR expansion stress in concrete would be taken by both the ligature and vertical steel bars. The fact that measured concrete vertical strain was very similar to that of horizontal strain indicates that the vertical and lateral expansion were equally restrained.

The strain developed in the CFRP wrapping reflects the AAR pressure of the concrete column. The pressure can be estimated by considering the system as a thin-walled cylinder with the thickness of the wrapping (t) subjected to internal pressure *p*, as shown in the sketch below



Schematic presentation of stress in thin-walled cylinder subjected to internal pressure.

For a unit length *l*, the force balance is $2rlp = 2tl\sigma_\theta$, where σ_θ is the stress developed in the CFRP. In the elastic range of the CFRP, the internal concrete expansion pressure (p) and the stress developed in CFRP (σ_θ) are expressed below; the strain developed in the wrapping (ε) depending on the elastic modulus of the wrapping.

$$p = \sigma_\theta \frac{t}{r} \quad \text{and} \quad \sigma_\theta = E_{wrap}\varepsilon,$$

The stress in each of the carbon fibre (CF) and epoxy materials can be calculated by the known modulus of elasticity and the measured strains, i.e.

$$\sigma_{CF} = E_{CF}\,\varepsilon \quad \text{and} \quad \sigma_{epoxy} = E_{epoxy}\varepsilon$$

The modulus of elasticity (E) of the wrapping, consisting of epoxy and carbon fibre, is given below, where A denotes the area of each material.

$$E_{wrap} = \frac{A_{CF}}{A_{con}} E_{CF} + \frac{A_{epoxy}}{A_{con}} E_{epoxy}$$

Thus the internal pressure, which can be considered as the pressure caused by the AAR expansion can be calculated as

$$p = \sigma_\theta \frac{t}{r} = \frac{t}{r} E_{wrap}\varepsilon$$

The thickness of the wrapping was measured, and the fraction of carbon fibre was calculated using the standard thickness of the CF sheet and the nominated number layers applied. Table 3 shows the expansion pressure calculated according to the CFRP strains measured in the last measurement.

The results in Table 3 indicate that columns wrapped at early age (2 months) developed AAR pressure of 0.67 - 1.46MPa, and that the stress in CFRP was 90 - 140MPa, being smaller for the higher stiffness wrapping (higher modulus or more layers). The latter suggests that AAR had developed to a lesser extent in the columns with 640 GPa wrapping. The above values of AAR pressure are comparable to the value of 1.5 MPa estimated earlier from the elongation of vertical bars before wrapping.

For the columns wrapped at later age, one year after the wrapping CFRP strains were between 190-430μm/m (stress 17-40MPa in the wrapping) and AAR pressure of 0.14-0.49MPa for the period after the wrapping. These values are much smaller in comparison with the columns wrapped at early age (Columns 7-10), which showed 460-1270 μm/m strain in the same period. This indicates that the AAR potential for the aggregate can be suppressed by early confinement. Figure 8 shows that early wrapping of columns suppresses the expansion of both the concrete and main steel bars, compared to columns without wrapping.

It should be noted that the estimation of pressure in the wrapping is only indicative because the strain measurements for CFRP showed large variations. Nevertheless, they demonstrate that high stiffness wrapping is more effective in confining AAR expansion. Therefore, the ratio between the thickness of wrapping and cross section of the column to be confined should be taken into consideration in the design of the wrapping.

Results of strain measurement show that, at the present time, the CFRP in Columns 7-10 has reached about 30% of its safe elongation, and the stress in the carbon fibre is very high, but well below its nominal tensile strength. However, the latter is determined using the standard coupon test, which may overestimate the actual strength of the material as applied in the field. Indeed, it has been reported [11-13] that the tensile strength of carbon fibre as determined by the standard coupon test was higher than that determined in concrete tests. This raises question on the safe, long term confinement afforded by CFRP in cases of ongoing, expansive AAR.

4 CONCLUSIONS

Ten reinforced circular columns (300mm x 1100mm), made with reactive aggregate, were confined, using two types of CFRP (240GPa and 640GPa modulus), to suppress AAR expansion. CFRP wrapping (1-3 layers) was applied on columns, (a): at the age of 2 months (cured under normal temperature), and (b:) at 530 days after some AAR expansion and cracking had occurred in the columns. Strain development was monitored for concrete, steel bars and CFRP wrap.

It was found that CFRP wrapping suppressed the progress of AAR whether applied at early or later ages. AAR-expansion after the wrapping was smaller in columns wrapped at later ages than those at early ages, due to smaller residual expansion in the former. The effect of wrapping with multiple layers of CFRP was not clear probably because of creep of the epoxy/ or slipping of CFRP layers at the 38C curing temperature.

The elongation of vertical steel bars started when concrete expansion exceeded about 400 micro-strains and the magnitude was approximately proportional to that of concrete. The strain of steel bars indicated an AAR expansion pressure of 1.5MPa.

For the columns wrapped at early ages, the strain of CFRP at age of two years indicates AAR expansion pressure of 0.6 to 1.5MPa. The consequent stress developed in CFRP (90 - 140MPa) was well below the tensile strength of the carbon fibre, which reached only about 30% of its elongation capacity. Further monitoring is required to verify whether the CFRP will be able to confine the AAR expansion to exhaustion.

The stress in the CFRP was smaller for the higher stiffness wrapping (higher modulus or more layers). This suggests that AAR developed to a lesser extent in the columns with higher stiffness wrapping. Therefore, higher stiffness wrapping may be more suitable to control the AAR expansion.

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Table1- Properties of CFRP Wrapping Materials

Name	Specific gravity	Modulus (GPa)	Thickness (mm)	Tensile strength (MPa)	Ultimate elongation (%)
MBRACE CF240/4400	1.7	240	0.235	3800	1.55
MBRACE CF640/2650	2.1	640	0.19	2650	0.4
MBRACE SATURANT (epoxy)		3	—		2.5

Table 2- Schedule of CFRP Wrapping

Column Number	Fabrication date	Wrapping scheme
1	28/10/2008	Reference column - no treatment
2	29/10/2008	1 layer of 240GPa CFRP at age of 1 year; actual age 540 days
3	30/10/2008	2 layers of 240GPa CFRP at age of 1 year; actual age 533 days
4	5/11/2008	3 layers of 240GPa CFRP at age of 1 year; actual age 539 days
5	6/11/2008	1 layer of 640GPa CFRP at age of 1 year; actual age 531 days
6	24/11/2008	2 layers of 640GPa CFRP at age of 1 year; actual age 513 days
7	15/12/2008	3 layer of 240GPa CFRP at age of 2 months; actual age 61 days
8	16/12/2008	2 layers of 240GPa CFRP at age of 2 months; actual age 60 days
9	17/12/2008	1 layer of 240GPa CFRP at age of 2 months; actual age 59 days
10	18/12/2008	1 layer of 640GPa CFRP at age of 2 months; actual age 70 days

Table 3- Concrete expansion pressure evaluated from the strain of CFRP wrapping

Column	CFRP type, layer and Thickness (mm)	A_{CF} / A_{conc}	CFRP Strain (μm/m) 04/2011	E_{CF} (GPa)	Stress, Carbon Fibre σ_{CF} (MPa)	Stress, Wrapping σ_θ (MPa)	AAR pressure, column p (MPa)
2	N1: 0.9	0.261	358	240	86	23	0.14
3	N2: 1.7	0.276	245	240	59	17	0.19

4	N3: 2.5	0.282	431	240	103	30	0.49
5	H1: 0.9	0.211	295	640	189	40	0.24
6	H2: 1.7	0.224	189	640	121	27	0.31
7	N3: 2.5	0.282	1277	240	306	89	1.46
8	N2: 1.7	0.276	1667	240	400	114	1.27
9	N1: 0.9	0.261	2153	240	517	140	0.82
10	H1: 0.9	0.211	832	640	532	114	0.67

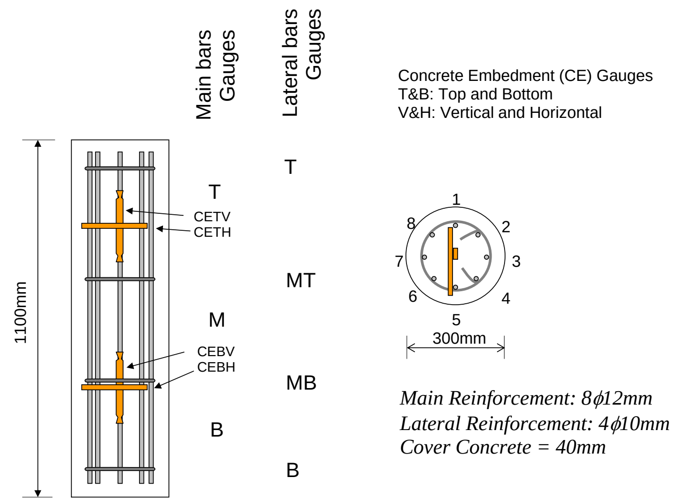

Figure 1- General design of columns and locations of various strain gauges.

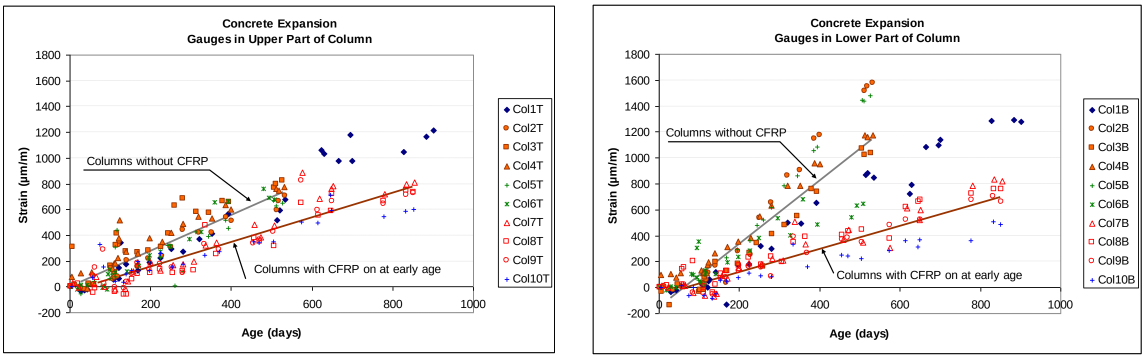

Figure 2- Expansion of columns with early CFRP wrapping compared to those without wrapping

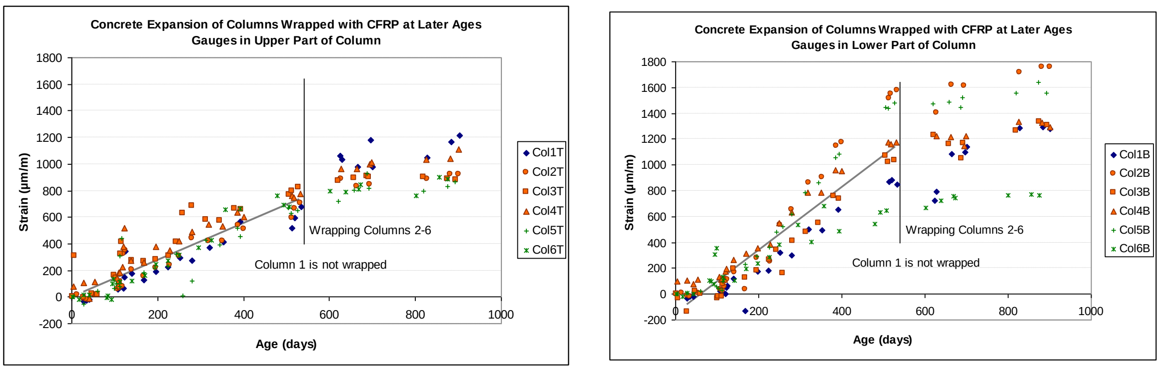

Figure 3- Expansion of columns with CFRP wrapping at later ages: Left (upper part), Right (lower part)

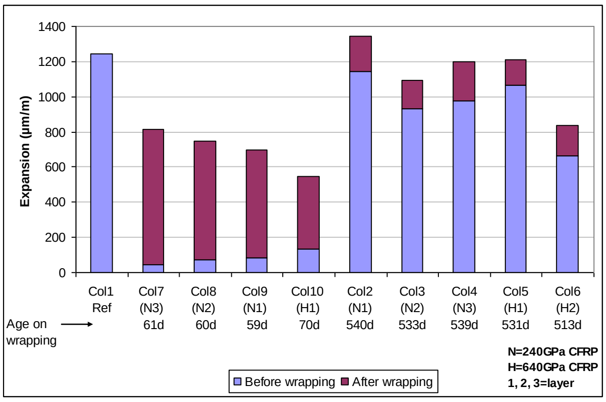

Figure 4- Average expansion of columns before wrapping and the total expansion at about 2.5 years

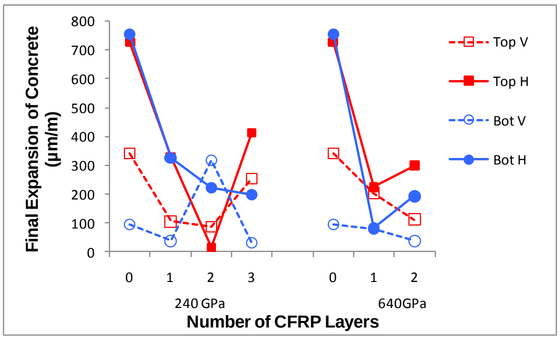

Figure 5- Net expansion of columns 2-6 since wrapping at later ages of 513-540 days

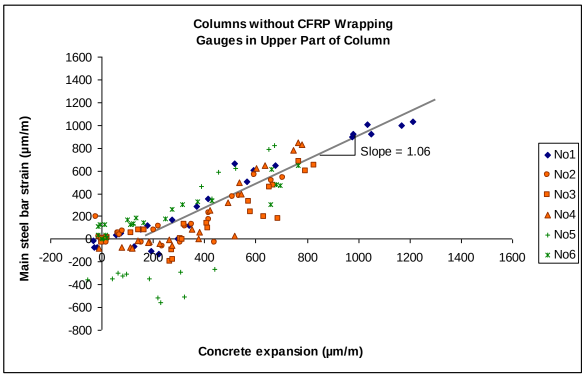

Figure 6- Correlation between expansion of main bars and concrete for upper parts of columns without CFRP

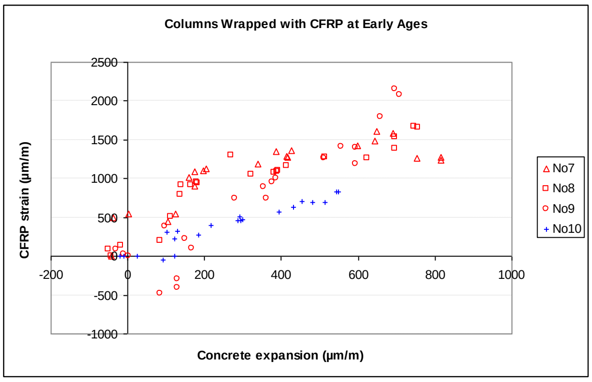

Figure 7- Correlation between expansion of CFRP and concrete; columns wrapped at early age

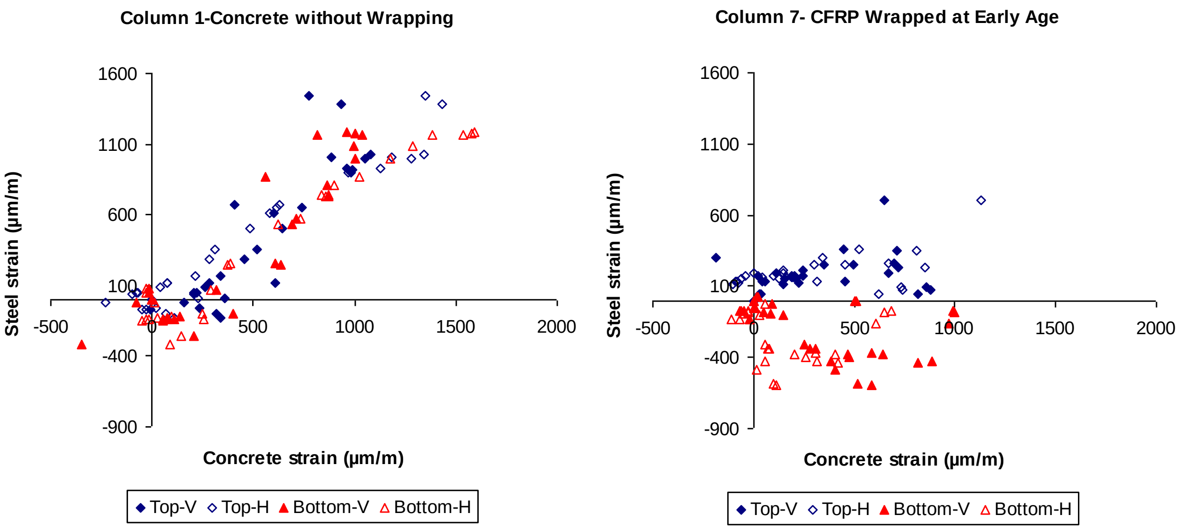

Figure 8- correlation between concrete expansion and strain development in vertical steel bars. Left: columns without wrapping; Right: columns wrapped with 3-layers of 240GPa CFRP at early age.