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# The Behaviour of Carbon Fibre Reinforced Polymer Confined Concrete Cylinders under High Temperature Exposure

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**Synopsis**: This study investigates the effect of temperature on the behaviour of concrete cylinders wrapped with Carbon Fibre Reinforced Polymer (CFRP). The study used nine concrete cylinders in three groups; the first group was exposed to room temperature of approximately 20ºC, the second group was exposed to a cyclic temperature with a temperature range of 20ºC to 70ºC, and the third group was exposed to a prolonged temperature of 70ºC. All cylinders were then tested to failure. The study indicated that ultimate strength of cylinders wrapped with one and two layers of CFRP are significantly unchanged after being exposed to 20ºC to 70ºC and 70°C. Deflection at ultimate load of cylinder wrapped with one layer of CFRP increased after being exposed 20ºC to 70ºC and 70°C while for cylinder wrapped with two layers of CFRP increased after being exposed to 70°C but significantly unchanged after being exposed to 20ºC to 70ºC. Ultimate deflection and total energy absorption of cylinders wrapped with one and two layers of CFRP decreased after being exposed to 20ºC to 70ºC and 70°C. Moreover displacement ductility of cylinders wrapped with one and two layers of CFRP increased after being exposed to 20ºC to 70ºC and 70°C.

Keywords: Carbon Fibre Reinforced Polymer, high temperatures, strength, energy absorption, ductility.

## 1. Introduction

Fibre Reinforced Polymer (FRP) is known as an excellent material for retrofitting, repairing and strengthening structural members. It is characterised by the following features: light weight material, corrosion resistant; available in various forms for field application, such as bar, sheet, strips and plate, and also available in long length thus eliminating the need for joints and splices; and can be cured within 24 hours when applied in the field.

Moreover, application of FRP to confine concrete members is widely used all over the world, due its high strength to weight ratio and ease of installation. When FRP is applied, it will lead to improving the strength of concrete members and it will increase their ductility dramatically, and reduce their maintenance compared to other methods such as attachment of steel to concrete and concrete jacket method.

However the behaviour of FRP confined concrete members has not been explored extensively especially in a situation of high temperature environment where solar gain could lead to a high concrete surface temperature. The maximum reported environment temperature applied for FRP confined concrete member is +45ºC. This temperature cannot represent the maximum temperature in countries such as Australia where some areas of Australia has had experienced temperatures more than +45ºC. It is also noticed that the global temperature tend to increase as a result of climate changes.

Therefore if the behaviour of FRP confined concrete members under high temperatures is known, the application of FRP confined concrete members can be used more confidentially in a wider range of temperature situation. This study investigates the effect of high temperature and cyclic temperature on the behaviour of FRP confined concrete cylinders under axial compression loading.

## 2. Review of Literature

El-hacha et al. (1) investigated the behaviour of plain concrete cylinders wrapped with FRP sheets subjected to a harsh environment such as high temperature, heating and cooling cycles, and prolonged heat temperature. The high temperature was represented by a temperature of +45ºC for 70 days, heating and cooling cycle was represented by a temperature of +23ºC to +45ºC for 33 cycles, and prolonged temperature was represented by a temperature of +45ºC for 70 days. Thirty six plain cylinders having 150 mm diameter and 300 mm height were cast and tested under axial compression loading until failure. Nine cylinders were unwrapped and used as control specimens and 24 cylinders were wrapped with 2 layers of

CFRP sheets. Half of the cylinders under heating and cooling cycle temperature were then subjected to freezing and thawing cycle (-18ºC to +23ºC) for 33 cycles and the others were submerged in fresh water at +23ºC for 33 days or salt water at +23ºC for 33 days. The study found that no significant difference of strength was observed for both wrapped and unwrapped specimens subject to heating and cooling cycle compared to the room temperature specimen. Slightly negative effect was monitored on the compressive strength of both wrapped and unwrapped specimens under freezing and thawing cycles as well as fresh and salt water immersion. The strength of wrapped concrete cylinders was observed not to decrease as a result of high temperature exposure.

Kabhari et al. (2) investigated the effect of extended freeze-thaw (dry) cycles on the response of both CFRP and GFRP reinforced FRP composite wrapped concrete. Cylinders made of 50 MPa having 152.4 mm diameter and 304.4. 8 mm height were cast and tested. After 28 days in a water tank, the cylinders were removed and wrapped with two types of FRP (CFRP and GFRP) and were placed in room temperature for one1 month before testing. Next the specimens were divided into two groups; the first group was stored at 22.5ºC and the others were subjected to 201 freeze-thaw cycles between 22.5ºC to -20ºC C. All specimens were tested until failure by axial compression loading. It was found that there was no significant change of ultimate strength of the wrapped cylinder after being exposed to freeze and thaw cycles and its stiffness was observed increasing compared to room temperature cylinders.

Homan and Sheikh (3) tested FRP tensile coupons and FRP single lap bonded specimen to investigate the durability of FRP composite and FRP reinforced concrete under various environmental conditions. The environmental condition was freeze-thaw cycles (between -18ºC to + 4ºC) and submerged into water, UV radiation, temperature variation (4 cycles/day between -20ºC to + 40ºC in dry chamber), alkaline solution, moisture (water submersion at 22ºC room temperature). It was concluded that all environmental condition had minimal effect on the mechanical properties of FRP composites. Freeze-thaw cycles and moisture exposure were observed as noticeable effects on the bond properties of single lap bonded specimen.

Karbhari and Eckel (4) tested eight cylinders made of 51.88 MPa concrete having 152.4 mm diameter and 304.8 mm height to investigate the effect of temperature on three different composite jackets subjected to temperature of 22.8ºC and -17.8ºC. After a curing period of 28 days, six specimens were wrapped with two layers of CFRP, GFRP, and AFRP using epoxy and were placed in a vacuum bag and cured inat room temperature for 36 hours. Next, the specimens were divided into two groups where each group consisted of one unwrapped specimen and three cylinders wrapped with two layers of CFRP, GFRP, and AFRP. All the specimens of the first group were exposed to a temperature of 22.8ºC for 60 days and the specimens of the second group were exposed to a temperature of -17.8ºC for 60 days. After being exposed to the temperature, all specimens were tested using axial compression load until failure. The research found that the compressive failure load of confined cylinder increases after being exposed to a temperature of -17.8ºC.

Karbhari (5) performed an experimental test on confined concrete exposed to extended freeze (both before and after moisture absorption) and freeze-thaw regimes in order to evaluate the effect caused by exposure, both neat resin (unreinforced resin matrix) specimens, and FRP composite when exposed to same environments as the confined concrete cylinders. Plain cylinders made of 41.4 MPa concrete having a size of 152.4 mm diameter and 304.8 mm height were cast and tested. After curing for 28 days, all cylinder moulds were removed and wrapped with 3 layers of CFR and then put into a chamber with temperature of 23ºC and 50% room humidity. Sample of neat resin and composite were fabricated and treated as confined cylinder specimens. Before being exposed to a number of cycles, a set of unconfined cylinders and confined cylinders and also unreinforced resin matrix and composite were tested under axial compression loading. Next, specimens were divided into three groups where one group was exposed to freeze environment, one was exposed to saturated freeze environment, and the other one was exposed to freeze-thaw environment. Specimens were exposed to freeze environment by placing them at a temperature of -18 ºC. Specimens were exposed to saturated freeze environment by immersing them in deionized water at 23ºC temperature for 25 days and then placing them at -18ºC temperature. Specimens were exposed to saturated freeze-thaw environment by immersing them in deionized water at 23ºC temperature for 25 days and then exposing them to a daily cycling between 20ºC to -18 ºC. Next all specimens were tested under axial compression loading. It was found that after being exposed to a prolonged temperature of -18ºC and freeze-thaw cycles (20ºC to -18ºC) after moisture, degradation of matrix and bonding between matrix and FRP were observed, resulting in a reduction of FRP composite confined concrete cylinders' strength. From previous studies, it seems that the region where the extreme temperature is more than 45$^0$ C needs to be investigated and also solar gain can lead to concrete temperatures being much higher than ambient. Some of regions such Australia have experienced very extreme temperatures where 50.7$^0$C was observed in 1950 (Australia Bureau of Meteorology (6)). Therefore there is a need to investigate the behaviour of FRP wrapped reinforced concrete members at higher temperatures above 45$^0$C. This study is a step in this direction.

## 3. Experimental Programme

Nine Cylinders having 100 mm diameter and 200 mm height made of 60 MPa concrete were cast and tested. One day after pouring, all cylinders were removed and submerged into a water tank for 28 days for hydration. After that the cylinders were dried and cleaned. Wrapping was done by mixing epoxy resin and hardener with a ratio of 1:5. The mixture dried up in room temperature after one day of application. For cylinders that were wrapped with 2 layers, the second layer was applied after 30 minutes of the application of the first layer. This length of time can protect the first layer from movement when the second layer was applied. The mechanism of wrapping can be seen in Figure 1.

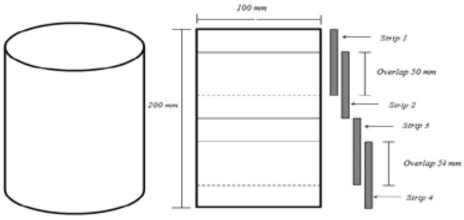

**Figure 1. Mechanism of Wrapping**

All cylinders were then divided in three groups, one group was kept at room temperature as reference, cycle temperature group, and prolonged temperature group. Cylinders in room temperature group were with a temperature of approximately 20$^0$C for 30 days; cylinders of the cycle temperature group were placed in an oven with a temperature of 70$^0$C for 1 day and then removed out of the oven and kept at room temperature of 20$^0$C for 1 day. This process was repeated for 30 days. The cylinders in the prolonged temperature group were placed in an oven with temperature of 70$^0$C for 30 days. Each group consisted of one unwrapped cylinder, one cylinder wrapped with one layer of CFRP, and one cylinder wrapped with two layers of CFRP. Details of the cylinders can be seen in Table 1.

**Table 1. Details of Cylinder**

| Temperature exposure | Unwrapped cylinder | Wrapped cylinder with | | Treatment | Length of treatment |
|---|---|---|---|---|---|
| | | 1 layer of CFRP | 2 layers of CFRP | | |
| 20$^o$C (room temp.) | 1 | 1 | 1 | Inside room with 20$^0$C | 30 days |
| Symbol | U0R | C1R | C2R | | |
| 20$^o$C to 70$^o$C (cycle temp.) | 1 | 1 | 1 | 1 day in oven with 70$^0$C and 1 day out oven with 20$^0$C | 30 days |
| Symbol | U0C | C1C | C2C | | |
| 70$^o$C (prolonged temp.) | 1 | 1 | 1 | Inside oven with 70$^0$C | 30 days |
| Symbol | U0P | C1P | C2P | | |

After temperature exposure, cylinders were tested in room temperature by the application of an axial concentric loading until failure. The strain-controlled loading was applied on the cylinder using a compression machine with capacity of 5000 kN at rate of 0.2 mm/s. Data obtained was load and axial deflection and was recorded every 2 seconds. All the tests were conducted at the Engineering Laboratories at the University of Wollongong.

## 4. Experimental Results

### *4.1. Unwrapped Cylinder (U0R, U0C, and U0P)*

The load-axial deflection curve of the unwrapped cylinders exposed to 20°C, 20°C to 70°C, and 70°C are presented in Figure 2.

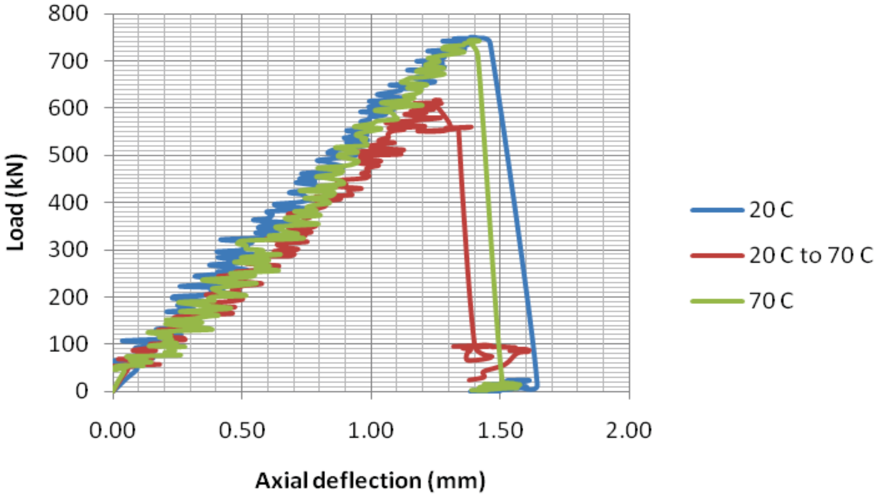

**Figure 2. Load-axial deflection of Unwrapped Cylinders**

### *4.2. Cylinders wrapped with one layer of CFRP (C1R, C1C, and C1P)*

The load-axial deflection curve of the cylinders wrapped with one layer of CFRP exposed to 20°C, 20°C to 70°C, and 70°C are presented in Figure 3.

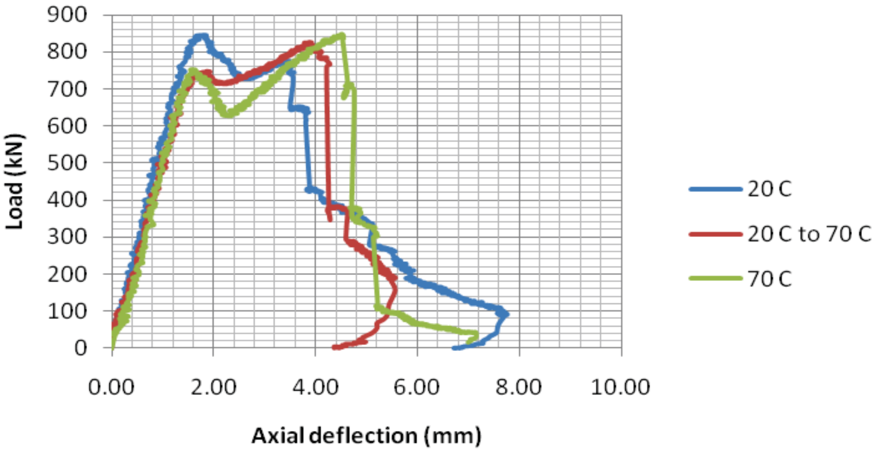

**Figure 3. Load-axial deflection of Cylinders wrapped with 1 layer of CFRP**

### *4.3. Cylinders wrapped with two layers of CFRP (C2R, C2C, and C2P)*

The load-axial deflection curve of the cylinder wrapped with two layers of CFRP exposed to 20°C, 20°C to 70°C, and 70°C are presented in Figure 4.

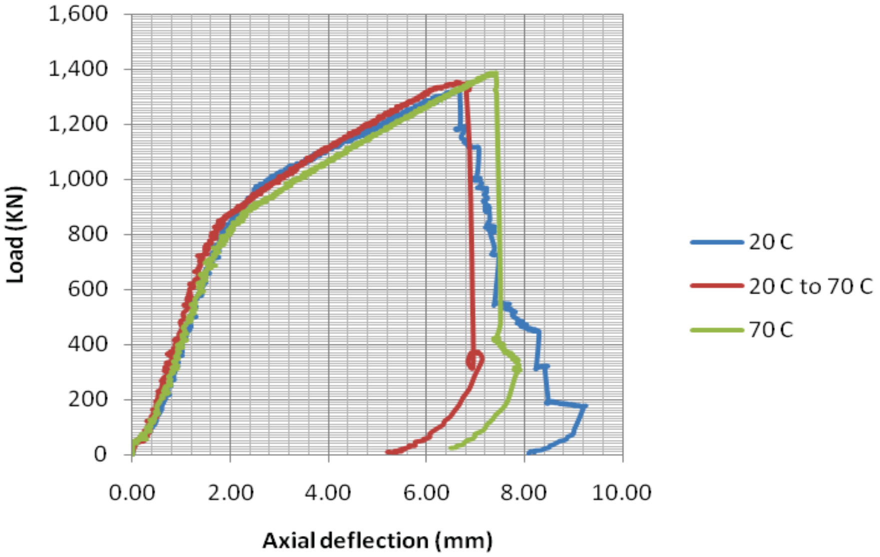

**Figure 4. Load-axial deflection of Cylinders wrapped with 2 layers of CFRP**

## 5. Analysis of Results

### *5.1. Ultimate Strength, Deflection, Energy absorption, and Ductility Characteristics*

### *5.1.1. Unwrapped Cylinders (U0R, U0C, and U0P)*

Table 2 shows the ultimate load, corresponding deflection, and ultimate deflection of the unwrapped cylinders. It can be seen that after being exposed to 20°C to 70°C, the ultimate strength, corresponding deflection, and ultimate deflection of the cylinder decreased while the ultimate load, corresponding deflection, and ultimate deflection of cylinders after being exposed to 70°C did not significantly change.

**Table 2. Test results of cylinders with no wrap**

| Temperature exposure | Ultimate Load (kN) | Deflection at ultimate load (mm) | Ultimate deflection (mm) |
|---|---|---|---|
| 20°C | 749.96 | 1.39 | 1.46 |
| 20°C to 70°C | 616.25 | 1.27 | 1.34 |
| 70°C | 742.14 | 1.42 | 1.42 |

Figure 5 presents the load-axial deflection curve of the cylinders after being exposed to 20°C, 20°C to 70°C, and 70°C. It was observed that after being exposed to 20°C to 70°C and 70°C, the load-axial deflection of the cylinder had similar trend to the cylinder after being exposed to 20°C where the ultimate load and ultimate deflection of cylinders after being exposed to 20°C to 70°C, and 70°C decreased.

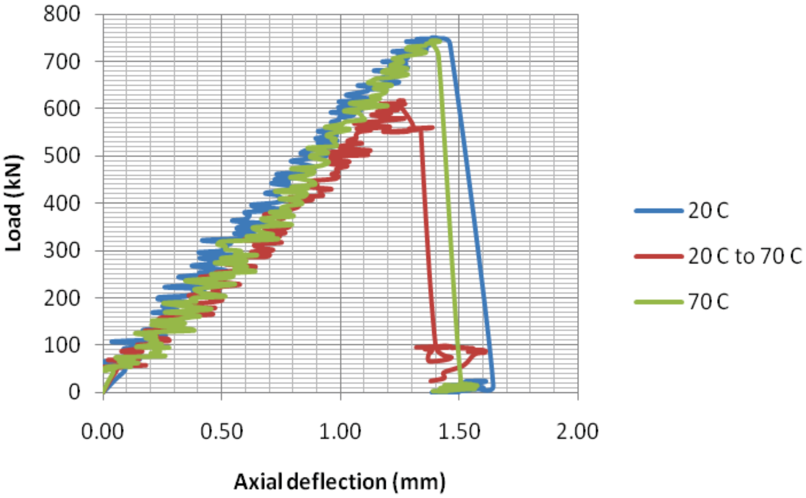

**Figure 5. Load-axial deflection curves of unwrapped cylinders**

Energy absorption is an important parameter for engineers to calculate the damage of any materials or structures caused by loading, assessing the residual strength of materials or structures after initial damage and in designing to protect the materials or structures after impact of any loading. Energy absorption of cylinders is presented in Table 3. It is clearly seen that after being exposed to 20°C to 70°C and 70°C, the capacity of cylinders to absorb energy at ultimate load as well as total energy decreased. The worst decrease was experienced by the cylinder after being exposed to 20°C to 70°C. It seems that energy absorption of cylinder after being exposed to 70°C decreased but its load capacity and deflection at ultimate load are significantly unchanged.

**Table 3. Comparison of energy absorption for unwrapped cylinders**

| Temperature exposure | Energy absorption at ultimate load (J) | Total energy absorption (J) | Improvement at ultimate load (%) | Improvement of total energy absorption (%) |
|---|---|---|---|---|
| 20°C | 4.22 | 4.28 | 0.00 | 0.00 |
| 20°C to 70°C | 2.75 | 3.04 | -34.85 | -28.89 |
| 70°C | 3.40 | 3.46 | -19.24 | -19.12 |

On other hand, as can be seen in Table 4, displacement ductility of cylinders after being exposed to 20°C to 70°C is not significantly changed and after being exposed to 70°C increased. The maximum increase was observed on the cylinder after being exposed to 70°C. Displacement ductility is derived from the ratio of displacement at yield load 85% of the maximum load or the ultimate load on the descending part to the yield displacement of the load-displacement curve.

**Table 4. Ductility results for unwrapped cylinders**

| Temperature exposure | Ductility (mm/mm) |
|---|---|
| 20°C | 1.13 |
| 20°C to 70°C | 1.14 |
| 70°C | 1.66 |

### *5.1.2. Cylinders wrapped with one layer of CFRP (C1R, C1C and C1P)*

As shown in Table 5, the ultimate strength of cylinders wrapped with one layer of CFRP after being exposed to 20°C to 70°C and 70°C are significantly unchanged. Meanwhile the deflection at ultimate load significantly increased both for cylinders after being exposed to 20°C to 70°C and 70°C but the ultimate deflection before cylinders collapse decreased.

**Table 5. Test results of cylinders with 1 layer of wrap**

| Temperature exposure | Ultimate Load (kN) | Deflection at ultimate load (mm) | Ultimate deflection (mm) |
|---|---|---|---|
| 20°C | 846.22 | 1.79 | 7.50 |
| 20°C to 70°C | 825.89 | 3.87 | 4.28 |
| 70°C | 848.88 | 4.51 | 5.14 |

Figure 6 shows load-axial deflection curves of cylinders after being exposed to 20°C, 20°C to 70°C, and 70°C. It was observed that the load-axial deflection of cylinders after being exposed to 20°C to 70°C and 70°C had different trend to the cylinder at 20°C. The ultimate load was observed at the first peak for cylinder at 20°C but on the second peak load for cylinder after being exposed to 20°C to 70°C and 70°C. The ultimate deflection that was reached by the cylinder after being exposed to 20°C to 70°C and 70°C was lower than the cylinder after being exposed to 20°C.

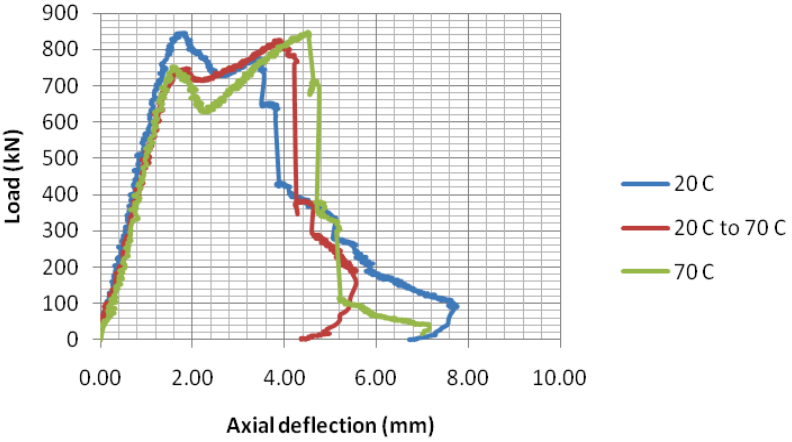

Figure 6. Load-axial deflection curves of cylinders with 1 layer of wrap

Table 6 shows a comparison of energy absorption of cylinders after being exposed to 20°C to 70°C, 70°C and cylinders after being exposed to 20°C. It is clearly seen that after being exposed to 20°C to 70°C and 70°C, energy absorption capacity of cylinders both at ultimate load and total energy absorption increased. The best energy absorption at ultimate load and total energy absorption was observed in cylinders after being exposed to 70°C. It is noted that from Figure 6, energy absorption at the first peak of cylinders after being exposed to 20°C to 70°C and 70°C decreased, but at the second and at total increased.

**Table 6. Comparison of energy absorption for cylinders with 1 layer of wrap**

| Temperature exposure | Energy absorption at ultimate load (J) | Total energy absorption (J) | Improvement at ultimate load (%) | Improvement of total energy absorption (%) |
|---|---|---|---|---|
| 20°C | 4.35 | 12.73 | 0.00 | 0.00 |
| 20°C to 70°C | 13.90 | 15.54 | 219.83 | 22.07 |
| 70°C | 17.36 | 18.77 | 299.31 | 47.45 |

As can be seen in Table 7, the displacement ductility of cylinders after being exposed to 20°C to 70°C and 70°C increased. The maximum increase was observed on the cylinder after being exposed to 70°C.

**Table 7. Ductility results for cylinders with 1 layer of wrap**

| Temperature exposure | Ductility (mm/mm) |
|---|---|
| 20°C | 1.49 |
| 20°C to 70°C | 2.95 |
| 70°C | 3.19 |

### *5.1.3. Cylinders wrapped with two layers of CFRP (C2R, C2C and C2P)*

Table 8 shows ultimate load, deflection at ultimate load, and ultimate deflection of cylinders wrapped with two layers of CFRP. It is clearly seen that after being exposed to 20°C to 70°C and 70°C, the ultimate strength and the deflection at ultimate load did not show a significant increase while the ultimate deflection increased after being exposed to 20°C to 70°C and decreased after being exposed to 70°C.

**Table 8. Test results of cylinders with 2 layers of wrap**

| Temperature exposure | Ultimate Load (kN) | Deflection at ultimate Load (mm) | Ultimate deflection (mm) |
|---|---|---|---|
| 20°C | 1324.99 | 6.64 | 9.04 |
| 20°C to 70°C | 1353.65 | 6.62 | 6.89 |
| 70°C | 1385.94 | 7.41 | 7.43 |

Figure 7 shows the load-axial deflection curve of cylinders 20°C, 20°C to 70°C, and 70°C. It was observed that after being exposed to 20°C to 70°C and 70°C, the load-axial deflection of cylinders had a similar trend to the cylinder at 20°C. The ultimate load increased after being exposed to 20°C to 70°C and 70°C but it is not significant. Meanwhile the ultimate deflection is unchanged for cylinder after being exposed to 20°C to 70°C and decreased for cylinder after being exposed to 70°C.

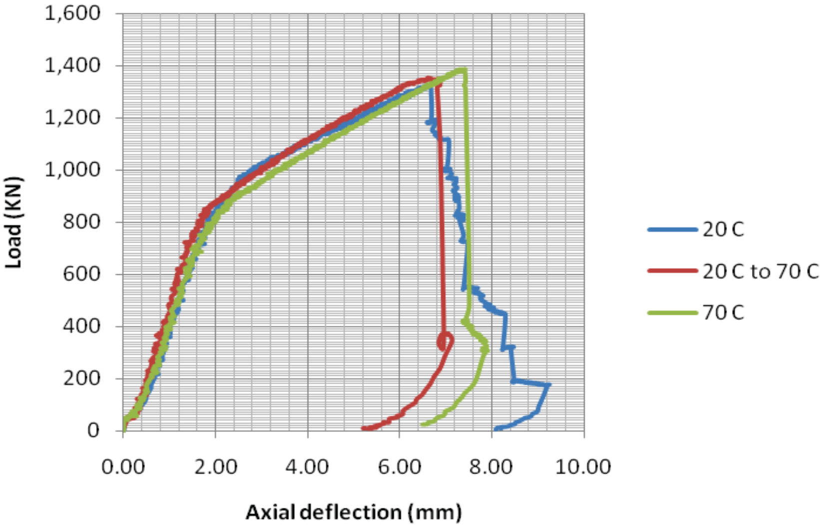

**Figure 7. Load-axial deflection curves for cylinders with 2 layers of wrap**

Table 9 presents a comparison of energy absorption of cylinders after being exposed to 20°C to 70°C, 70°C, and cylinder after being exposed to 20°C. It is obvious that after being exposed to 20°C to 70°C and 70°C, energy absorption at ultimate load and total energy absorption capacity of the cylinders decreased. The worst decrease in energy absorption was observed in the cylinder after being exposed to 20°C to 70°C. All cylinders experienced sudden failure after ultimate load achieved.

**Table 9. Comparison of energy absorption for cylinders with 2 layers of wrap**

| Temperature exposure | Energy absorption at max. load (J) | Total energy absorption (J) | Improvement at max. load (%) | Improvement of total energy absorption (%) |
|---|---|---|---|---|
| 20°C | 42.68 | 51.57 | 0.00 | 0.00 |
| 20°C to 70°C | 32.79 | 34.02 | -23.16 | -34.03 |
| 70°C | 34.61 | 34.71 | -18.91 | -32.69 |

Displacement ductility of cylinders after being exposed to 20°C to 70°C and 70°C increased as presented in Table 10. The maximum increase was observed in cylinder after being exposed to 20°C.

**Table 10. Ductility results for cylinders with 2 layers of wrap**

| Temperature exposure | Ductility (mm/mm) |
|---|---|
| 20°C | 3.62 |
| 20°C to 70°C | 4.36 |
| 70°C | 4.65 |

## 6. Conclusions

Based on findings of this study, the following conclusions are drawn:

1. The ultimate strength, deflection at ultimate load, and ultimate deflection of unwrapped cylinder decreased after being exposed to 20°C to 70°C and are significantly unchanged after being exposed to 70°C. The energy absorption of unwrapped cylinder after being exposed to 20°C to 70°C and 70°C decreased. Moreover the displacement ductility of unwrapped cylinder is not significantly increased after being exposed to 20°C to 70°C while it increased after being exposed to 70°C.

2. The ultimate strength of the cylinder wrapped with one layer of CFRP decreased after being exposed to 20°C to 70°C but it is significantly unchanged after being exposed to 70°C. Deflection at ultimate load of cylinder wrapped with one layer CFRP increased after being exposed to 20°C to 70°C and 70°C but its ultimate deflection decreased. The energy absorption both at ultimate load and at total and displacement ductility of cylinder wrapped with one layer of CFRP increased after being exposed to 20°C to 70°C and 70°C.

3. The ultimate strength and deflection at ultimate load of cylinder wrapped with two layers of CFRP are not significantly increase, while the ultimate deflection decreased after being exposed to 20°C to 70°C and 70°C. The energy absorption and displacement ductility of cylinder wrapped with two layer of CFRP increased after being exposed to 20°C to 70°C and 70°C.

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