REPAIR OF CONCRETE CYLINDERS WRAPPED WITH CARBON FIBRE REINFORCED POLYMER UNDER COMPRESSION

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ABSTRACT

This study examines normal concrete cylinders, 150mm in diameter and 300mm in height, of cylinder compressive strengths 25MPa and 35MPa, with and without carbon fibre reinforced polymer (CFRP) wrap, subjected to compression to assess the increase of strength that may be realized on account of the CFRP wrap. In addition companion cylinders that were damaged to about 70% to 75% of the compressive strength of the control cylinders and thereafter wrapped (repaired) with CFRP and again subjected to monotonic and cyclic compression loading to assess the increase in compressive strength of the repaired cylinders. It was observed that the cylinders which were undamaged and wrapped with CFRP failed at a higher load when compared to the control cylinders due to confinement of concrete mobilized by the CFRP wrap. The concrete cylinders which were damaged to about 70% to 75% of the compressive strength of the control cylinder and wrapped (repaired) with CFRP and again subjected to compression loading failed at a load greater than the load at which the control cylinders had failed at. This observation showed that the original compressive strength was restored for the damaged cylinders after repair. From the results it was observed that good confinement was mobilized by the CFRP wrap and CFRP is an effective repair material. Similar enhancement in the fatigue life characteristics were also observed for cylinders which were pre damaged under cyclic compression, repaired with CFRP wrap and thereafter subjected to cyclic compression loading. Studies on increase in fatigue life of thermally damaged concrete cylinders of 25MPa cylinder compressive strength repaired with CFRP wrap after cooling and thereafter subjected to cyclic compression has also been presented in this paper.

INTRODUCTION

Reinforced concrete (RC) structures such as buildings, bridge piers [2] in RC bridges and other RC structural elements like beams, columns and slabs in RC structures undergo damage due to earthquakes, accidental overloads and thermal damage due to fire. Repair is a strategy used to strengthen a damaged or aged structure to its original strength by utilizing suitable repair materials which are available. Carbon fibre reinforced polymer (CFRP) is one of the efficient materials for repair of damaged concrete structures because of its high strength, low weight and the ease with which CFRP sheets can be handled with and installed on the damaged structure by gluing it to the damaged component with the help of a epoxy resin. This paper studies the behavior of concrete cylinders of 25MPa and 35MPa cylinder compressive strengths, 150mm in diameter and 300mm in height, with and without CFRP[1,3,6,7] wrap subjected to compression to assess the increase of strength on account of the repair by CFRP wrap. Companion concrete cylinders were damaged to about 70% to 75% of the compressive strength of the control cylinders and thereafter wrapped (repaired) with CFRP and again subjected to monotonic and cyclic loading in compression to assess the increase in compressive strength and fatigue life of the repaired cylinders. It was observed that the cylinders which were undamaged and wrapped with CFRP, failed at a higher compressive load when compared to the control cylinders due to confinement of concrete mobilized by the CFRP wrap. Another set of concrete cylinders were damaged under monotonic compression to about 70% to 75% of the compressive strength of the control cylinders and thereafter wrapped (repaired) with CFRP and again subjected to monotonic and cyclic loading in compression to assess the increase in compressive strength and fatigue life of the repaired cylinders. It was observed that the cylinders after repair failed at a load which was slightly greater than the load at which the control cylinders had failed at, showing that the original compressive strength was restored for the damaged cylinders after repair. Increase in fatigue life [1, 2, 5 and 10] carrying capacity of concrete cylinders of 25MPa cylinder compressive strength has been presented in this study. To start with control concrete cylinders of 25MPa cylinder compressive strength was subjected to cyclic loading in compression without CFRP wrap. Concrete cylinders of 25MPa compressive strength which were undamaged and wrapped with 1 layer of CFRP was subjected to cyclic compression [1, 2, 3, 5 and 10] to access its fatigue life. Another set of concrete cylinders of the same cylinder strength as specified above were pre damaged under cyclic compressive load up to 60% to70% of the number of cycles the control concrete cylinders had failed at and thereafter 1 layer of CFRP
wrapping was done to the damaged cylinders and the test was continued to assess the fatigue life of the damaged cylinders repaired with CFRP wrap subjected to cyclic loading. Similar enhancement in fatigue life of concrete cylinders was observed for concrete cylinders of 25MPa cylinder compressive strength which were thermally damaged [4, 8, 9] by exposing the cylinders to a temperature of 550 deg C for duration of 4 hours which was later cooled to room temperature and wrapped with 1 layer of CFRP and thereafter was subjected to cyclic compression loads. The CFRP used was in a fabric form with 0 – 90˚ orientation of the fibres. One layer of CFRP was adhered to the concrete cylinder surface with help of an epoxy resin adhesive. The undamaged CFRP wrapped concrete cylinders and damaged CFRP wrapped concrete cylinders were subjected to monotonic and cyclic compression loads only after the epoxy resin adhesive had dried completely under room temperature. Properties of CFRP and the epoxy resin after 7 days of curing (drying) at 25°C room temperature is given in table 1 respectively.

<table>
<thead>
<tr>
<th>Properties of CFRP</th>
<th>Properties of Epoxy</th>
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<tr>
<td>Tensile Strength</td>
<td>600MPa</td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>420MPa</td>
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<tr>
<td>Young’s Modulus</td>
<td>50GPa</td>
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<tr>
<td></td>
<td>350 – 400 Kg / cm²</td>
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<td>800 – 1200 Kg / cm²</td>
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The strains on the concrete surface of the cylinders and on the CFRP were recorded with the help of electrical strain gauges which were adhered to the surfaces of concrete (internal – strain gauge adhered to concrete surface enclosed inside the CFRP) and CFRP (on the surface of the CFRP).

Control Concrete Cylinders Of 25MPa and 35MPa Cylinder Compressive Strengths
Concrete cylinders of 25MPa and 35MPa cylinder compressive strength which were cured in water for 28 days without CFRP wrap was subjected to monotonic compression. The control concrete cylinders were tested under monotonic compression loading to access the ultimate compressive strength (σu in MPa) at failure. The ultimate compressive strength of the control cylinders was required for calculating and fixing the maximum limit of load/stress value up to which the damaged concrete cylinders would be loaded in monotonic and cyclic compression. The stress strain response of the control concrete cylinders of 25MPa and 35MPa cylinder compressive strengths under monotonic compression loading are shown in Fig. 1a and Fig. 1b respectively. Fig. 2a shows the test setup for the concrete cylinders. Fig. 2b shows a concrete cylinder wrapped with CFRP with internal strain gauges adhered to the concrete enclosed by the CFRP wrap.

![Stress Strain in Axial Compression: Concrete Cylinder Strength : 25MPa](image1)

(a) 25MPa control cylinder compressive strength

![Stress Strain in Axial Compression : Concrete Cylinder Strength : 35MPa](image2)

(b) 35MPa control cylinder compressive strength

Fig. 1: Stress strain response of the control concrete cylinders of 25MPa and 35MPa cylinder compressive strengths under monotonic compression loading
Undamaged Concrete Cylinders Of 25MPa and 35MPa Cylinder Compressive Strengths Subjected To Monotonic Compression

Undamaged concrete cylinders of 25MPa and 35MPa cylinder compressive strengths which were cured in water for 28 days and later wrapped with 1 layer of CFRP was subjected to monotonic compression. The undamaged concrete cylinders which were wrapped with 1 layer of CFRP [3, 6, 7] exhibited a higher compressive strength when compared to the results of control concrete cylinders. The stress strain response of the undamaged concrete cylinders of 25MPa and 35MPa cylinder compressive strengths with CFRP wrap subjected to monotonic compression loading are shown in Fig. 3 and Fig. 4 respectively. In Figs. 3a and 4a internal refers to the stress strain response of the concrete which is enclosed within the CFRP wrap. In Fig. 3b and 4b external refers to the stress strain response of the CFRP.

(a) Stress Strain response of concrete(Internal)                (b) Stress Strain response of CFRP(External)
Fig. 3 Stress strain response of the undamaged concrete cylinders of 25MPa cylinder compressive strength with CFRP wrap subjected to monotonic compression loading

(a) Stress Strain response of concrete(Internal)                (b) Stress Strain response of CFRP(External)
Fig. 4 Stress strain response of the undamaged concrete cylinders of 35MPa cylinder compressive strength with CFRP wrap subjected to monotonic compression loading
Damaged Concrete Cylinders Of 25MPa and 35MPa Cylinder Compressive Strengths Subjected To Monotonic Compression

Concrete cylinders of 25MPa and 35MPa cylinder compressive strengths were pre damaged under monotonic compression loading up to about 70% to 75% of the compressive strength of the control cylinder under monotonic compression after which the load was released. These pre damaged concrete cylinders were wrapped (repaired) with 1 layer of CFRP[3, 6, 7] and again subjected to monotonic compression loading. It was observed that many cracks had developed on the surface of the damaged concrete cylinders while releasing the load after subjecting these cylinders to damage by monotonic compression. The damaged cylinders after repair failed at a load which was slightly greater than the stress at which the control cylinders had failed at. The stress strain response of the repaired concrete cylinders of 25MPa cylinder compressive strength which were pre damaged upto 70% to 75% of the compressive strength of the control cylinders and wrapped with CFRP and thereafter subjected to monotonic compression is shown in Fig. 5. Stress strain response of the repaired concrete cylinders of 35MPa cylinder compressive strength which were pre damaged upto 70% to 75% of the compressive strength of the control cylinders and wrapped with CFRP and thereafter subjected to monotonic compression is shown in Fig. 6. In Figs. 5a, and 6a internal refers to the stress strain response of the concrete which is enclosed within the CFRP wrap. In Fig. 5b, and 6b external refers to the stress strain response of the CFRP.

Fig. 5 Stress strain response of the repaired concrete cylinders of 25MPa cylinder compressive strength which was pre damaged upto 70% to 75% of the compressive strength of the control cylinders and wrapped with CFRP and thereafter subjected to monotonic compression loading

Fig. 6 Stress strain response of the repaired concrete cylinders of 35MPa cylinder compressive strength which was pre damaged upto 70% to 75% of the compressive strength of the control cylinders and wrapped with CFRP and thereafter subjected to monotonic compression loading
CONCRETE CYLINDERS OF 25MPa CYLINDER COMPRESSIVE STRENGTH WITH AND WITHOUT CFRP WRAP SUBJECTED TO CYCLIC COMPRESSION

Control Concrete Cylinders Of 25MPa Cylinder Compressive Strength Subjected To Cyclic Compression
The cyclic load in compression was applied as 60%\(\sigma_u\) ± 30%\(\sigma_u\), with a loading rate of 2kN/sec and at a frequency of 3Hz. Where\(\sigma_u\) is the ultimate compressive stress at which the control cylinders of 25MPa cylinder compressive strength had failed under monotonic compression loading. The control concrete cylinder of 25MPa cylinder compressive strength without CFRP wrap subjected to cyclic compression loading failed at 16,970 cycles. The stress strain behavior of the control concrete cylinder (25MPa) subjected to cyclic compression loading is shown in Fig. 7.

Undamaged Concrete Cylinders Wrapped With CFRP Subjected To Cyclic Compression
Concrete cylinders of cylinder compressive strengths 25MPa which were undamaged and wrapped with CFRP was subjected to cyclic loading in compression. The cyclic loading[1, 2, 3, 5, 10] in compression was applied on the undamaged concrete cylinders with CFRP as 60% of\(\sigma_u\) ± 30% of\(\sigma_u\) with a loading rate of 2kN/sec and at a frequency of 3Hz. Where\(\sigma_u\) is the ultimate compressive stress at which the control cylinders of 25MPa cylinder compressive strength had failed under monotonic compression loading. The undamaged concrete cylinder of cylinder compressive strength 25MPa wrapped with CFRP failed at 24,023 cycles. The undamaged concrete cylinders wrapped with CFRP subjected to cyclic loading failed without warning by sudden rupture of the CFRP with a bursting sound. The stress strain response of undamaged concrete cylinder of 25MPa cylinder compressive strength with CFRP wrap subjected to cyclic compression loading is shown in Fig. 8.

(a) Stress Strain response of concrete(Internal)  (b) Stress Strain response of CFRP(External)
Fig. 8 Stress strain response of undamaged concrete cylinder of 25MPa cylinder compressive strength with CFRP wrap subjected to cyclic compression loading.
Damaged Concrete Cylinders Wrapped With CFRP Subjected To Cyclic Compression

Concrete cylinders of cylinder compressive strengths 25MPa were damaged up to 60% to 70% of the number of cycles the control concrete cylinders had failed at. These cylinders which were pre damaged under cyclic loading [1, 2, 3, 5 10] was first wrapped with 1 layer of CFRP and thereafter was subjected to cyclic compression loading. The cyclic loading in compression was applied on the repaired cylinders with CFRP as 60% of \(\sigma_u \pm 30\% \text{ of } \sigma_u\) with a loading rate of 2kN/sec and at a frequency of 3Hz.

Before CFRP Repair:
The concrete cylinders were subjected to cyclic compression loading of up to 60% to 70% of the number of cycles the control concrete cylinders had failed at for pre damaging them prior to CFRP wrapping (repair):
Concrete cylinders of cylinder compressive strength of 25MPa was subjected to cyclic loading up to 10,000 cycles. The loading had to be released at 10,000 cycles, because many cracks had developed on the surface of these cylinders.

After CFRP Repair:
The damaged concrete cylinder of cylinder compressive strength 25MPa repaired by wrapping it with 1 layer of CFRP [3, 6, 7] failed at 10,377 cycles. The damaged concrete cylinders wrapped with CFRP subjected to cyclic loading failed by giving sufficient warning such as cracking sound of concrete and with slow opening of the CFRP which had ruptured by tearing vertically. The stress strain response of the pre damaged concrete cylinder of 25MPa cylinder compressive strength repaired with CFRP wrap and thereafter subjecting the cylinder to cyclic compression loading is shown in Fig. 9.

THERMALLY DAMAGED CONCRETE CYLINDERS: CONCRETE CYLINDERS OF 25MPA CYLINDER COMPRESSIVE STRENGTH EXPOSED TO A TEMPERATURE OF 550 DEGREES CELCIUS FOR DURATION OF FOUR HOURS WITH AND WITHOUT CFRP WRAP SUBJECTED TO CYCLIC COMPRESSION

Thermally Damaged Concrete Cylinders Of 25MPa Cylinder Compressive Strength Exposed To A Temperature of 550 Deg C Without CFRP Subjected To Cyclic Compression
Concrete cylinders which were not wrapped with CFRP [3, 6, 7] and was thermally damaged [4, 8, 9] by exposing these cylinders to a temperature of 550 deg C for duration of four hours in a furnace. These cylinders were allowed to cool up to room temperature and thereafter subjected to cyclic compression loading of 36% \(\sigma_u \pm 12\% \text{ of } \sigma_u\), with a
loading rate of 2kN/sec and frequency of 3Hz. Where \( \sigma_u \) is the ultimate compressive strength of control concrete cylinders of 25 MPa cylinder compressive strength subjected to monotonic loading. The thermally damaged concrete cylinder of cylinder compressive strength 25MPa without CFRP wrap which was exposed to 550 deg C for duration of 4 hours failed after 14,700 cycles. Fig. 10 shows the stress-strain response of the thermally damaged concrete cylinder of cylinder compressive strength 25MPa without CFRP wrap, which was exposed to 550 deg C for duration of 4 hours, cooled up to room temperature and thereafter subjected to cyclic compression loading.

![Stress-strain response of the thermally damaged concrete cylinder of cylinder compressive strength 25MPa without CFRP wrap, which was exposed to 550 deg C for 4 hours, cooled up to room temperature and thereafter subjected to cyclic compression loading.](image)

Thermally Damaged Concrete Cylinders Of 25MPa Cylinder Compressive Strength Exposed To A Temperature of 550 Deg C Wrapped With CFRP After Cooling And Subjected To Cyclic Compression

Concrete cylinders which were thermally damaged \([4, 8, 9]\) by exposing the cylinders to a temperature of 550 deg C for duration of four hours in a furnace. These cylinders were allowed to cool up to room temperature and wrapped with 1 layer of CFRP\([3, 6, 7]\) wrap after cooling, and was thereafter subjected to cyclic compression loading of \(52\% \sigma_u \pm 26\% \sigma_u\), with a loading rate of 2kN/sec and frequency of 3Hz. Where \( \sigma_u \) is the ultimate compressive strength of control concrete cylinders of 25 MPa cylinder compressive strength subjected to monotonic loading. The thermally damaged concrete cylinder of cylinder compressive strength 25MPa that was exposed to a temperature of 550 deg C for duration of 4 hours and later repaired with 1 layer of CFRP wrap after cooling failed after 20,900 cycles when subjected to cyclic compression loading. Fig. 11 shows the stress-strain response of the thermally damaged concrete cylinder of cylinder compressive strength 25MPa that was exposed to a temperature of 550 deg C for duration of 4 hours and later wrapped with CFRP after cooling and thereafter subjected to cyclic compression loading.

![Stress-strain response of the thermally damaged concrete cylinder of cylinder compressive strength 25MPa that was exposed to a temperature of 550 deg C for duration of 4 hours and later wrapped with CFRP after cooling and thereafter subjected to cyclic compression loading.](image)

(a) Stress Strain response of concrete(Internal) (b) Stress Strain response of CFRP(External)

Fig. 11 Stress-strain response of the thermally damaged concrete cylinder of cylinder compressive strength 25MPa that was exposed to a temperature of 550 deg C for duration of 4 hours and later wrapped with CFRP after cooling and thereafter subjected to cyclic compression loading.
CONCLUSION

- Concrete Cylinders of 25MPa and 35MPa cylinder compressive strengths subjected to monotonic loading:
  1) The undamaged cylinders with 1 layer of CFRP wrap failed at a higher value of stress than the corresponding control cylinders by sudden rupture of CFRP. There was a strength increase of 40% and 28.5% for undamaged concrete cylinders with CFRP wrap of 25MPa and 35MPa cylinder compressive strengths respectively when compared to the control concrete cylinders due to good confinement provided by the CFRP.
  2) The damaged cylinders repaired with 1 layer of CFRP wrap failed at a value of stress less than the undamaged CFRP wrapped cylinders but greater than the stress value corresponding to the control concrete cylinders failed, as observed in Fig. 5 for 25MPa cylinder compressive strength and Fig. 6 for 35MPa cylinder compressive strength cylinders respectively. These observations show that, good confinement provided by the CFRP to the concrete in compression was the reason for the original compressive strength being restored for the pre damaged cylinders after repair. These pre damaged cylinders after repair with 1 layer of CFRP wrap failed with crackling sound of concrete enclosed within the CFRP, and by slow opening of CFRP which opened by tearing vertically.

- Concrete Cylinders of 25MPa compressive strengths subjected to cyclic loading:
  1) The control cylinder without CFRP wrapping failed at 16,970 number of cycles.
  2) The undamaged CFRP wrapped cylinder failed at higher number of cycles (24,023 cycles) when compared to the fatigue life of the control concrete cylinder (16,970 cycles) for the same loading range accounting to nearly a 41% increase in the fatigue life due to good confinement provided by the CFRP to the concrete.
  3) The damaged cylinder repaired with CFRP wrap failed at 10,377 number of cycles after repair with sufficient warning before failure by cracking sound of concrete and slow opening of CFRP which opened by tearing vertically. This same cylinder was priorly damaged upto 10,000 cycles with excess cracks before CFRP repair. Though this cylinder being extensively damaged with cracks did not fail immediately after application of cyclic loading and performed reasonably well due to confinement provided by the CFRP accounting to nearly a 40% drop in the fatigue life after repair when compared to the fatigue life of the control cylinder.
  4) Concrete cylinders exposed to a temperature of 550 deg C for 4 hours had developed many cracks due to thermal damage and the fatigue life of these cylinders without CFRP was 14,700 cycles accounting to nearly a 13.37% drop in the fatigue life when compared to the fatigue life of the control cylinder. Another set of companion cylinders which were exposed to 550 deg C for 4 hours wrapped with CFRP after cooling exhibited a fatigue life of 20,900 cycles accounting to nearly a 23.15% increase in the fatigue life after repair when compared to the fatigue life of the control cylinder. On the whole the enhancement in the strength and fatigue life of pre damaged cylinders was due to good confinement provided by only 1 layer of CFRP wrap to the concrete showing that the repair was effective.

REFERENCES