FLEXURAL DUCTILITY OF PREFABRICATED CAGE REINFORCED STEEL - CONCRETE COMPOSITE BEAMS

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ABSTRACT

The present study investigated the flexural response and ductile behaviour of Prefabricated Cage Reinforced Concrete (PCRC) beams. The Prefabricated Cage System (PCS) is fabricated by perforating hollow cold formed steel tubes or steel sheets. The resulting PCS acts as transverse and longitudinal reinforcing steel, working compositely with the surrounding concrete to resist the applied loads. This new and innovative system eliminates some of the weaknesses and detailing problems inherent in traditional Reinforced Concrete Construction. Nine beam specimens reinforced with Prefabricated Cage System were tested under monotonic loading. The effects of thickness of cold formed steel sheet and Grade of Concrete on parameters such as moment curvature, load deflection, ductility and energy absorption were experimentally determined. All beams exhibited considerable amount of deflection, which provide ample warning to the imminence failure. Final failure of PCRC beams were found to occur in pure bending region. The results reveal that PCRC beams show better ductile performance and energy absorption capacity due to the confinement provided by PCS. Displacement and curvature ductility factor for all beams were found and discussed in this paper.

Keywords: PCRC Beam; displacement ductility factor; curvature ductility factor; prefabricated cage; energy absorption capacity

1. INTRODUCTION

Construction time plays a vital role as it affects the life cycle cost of the project. In reinforced concrete system, time consumed to cut, bend and tie the reinforcement bar is more, moreover in heavily reinforced sections, it may be extremely difficult to assemble the reinforcement. During construction of structures and bridges with very heavy traffic, project completion time is more important. The Prefabricated Cage System eliminates these difficulties and can play a vital role in fast track construction against the time consuming conventional process [6,7,8].

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The Prefabricated Cage Reinforced Concrete beams are produced by cutting out uniform rectangular openings on a cold formed steel sheet or tube. The vertical continuous strips perform the function of stirrups, while the horizontal strips act as main longitudinal reinforcement. Since the PCRC beams are fabricated in industries using CNC cutting, better quality control can be maintained.

In PCRC beams the core concrete confined by prefabricated cage system delays the microcracking mechanism and limits crack propagation, thus significantly improving the ductility and energy absorption capacity [2,3,13]. Ductility of a structure is one of the most important factors affecting its seismic performance and also the gap between the actual and design lateral forces is narrowed down by providing ductility in the structure [10,12,14,16]. The ability of a structural member to absorb energy is an important factor in the overall performance of structural elements. This paper discusses the moment curvature characteristics, curvature ductility and energy absorption capacity of PCRC beams.

2. RESEARCH SIGNIFICANCE

The studies carried out on the steel-concrete composite beams based on the available literatures [1,4,5,15,17], clearly indicates that so far, significant work has not been carried out on composite beams reinforced with prefabricated cage system. The purpose of this paper is to investigate the effect of grade of concrete, thickness of cold formed steel sheet, profile of prefabricated cage system (number of openings in tension reinforcement) to broaden the scope of application of PCRC beams. This paper provides information regarding (i) Deformation characteristics such as moment - curvature, load versus strain (ii) Ductility and energy absorption capacity of PCRC beams.

2.1 Experimental Program

2.1.1 Test Variables

The primary variables considered in the program included 1) thickness of cold formed steel sheet 1.6mm, 2mm and 2.5mm (percentage of tensile steel reinforcement ratio varied between 0.84% and 1.34%) 2) Compressive strength of concrete (23.05MPa, 27.21MPa and 33.78MPa).

2.1.2 Test Specimens

A total of nine series of PCRC beams were tested. All specimens have a clear span of 2.08m and rectangular cross section of 150mm x 200mm reinforced with PCS. The specimens were named J, K, L, M, N, O, P, Q and R.

Table 1 shows the dimensions of specimens. Specimen J was designed as a PCRC beam with cold formed steel sheet of thickness 1.6mm (Tensile reinforcement ratio of 0.84%). The compressive strength of specimen J is 23.05N/mm². Specimens M, P were designed with the same tensile reinforcement area as in specimen J. Only the compressive strength of the specimen M and P were increased to 27.21 N/mm² and 33.78 N/mm² respectively versus 23.05 N/mm² for specimen J.

Specimen K was designed as a PCRC beam with cold formed steel sheet of thickness 2mm (tensile reinforcement ratio of 1.06%). The compressive strength of specimen K is 23.05N/mm². Specimens N, Q were designed with the same tensile reinforcement area as in
specimen K. Only the compressive strength of the specimen N and Q were increased to 27.21 N/mm² and 33.78 N/mm² respectively versus 23.05 N/mm² for specimen K.

Table 1: Beam details and test parameters

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Beam Id</th>
<th>t (mm)</th>
<th>Compressive strength of concrete (N/mm²)</th>
<th>% of steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>J</td>
<td>1.6</td>
<td>23.05</td>
<td>0.84</td>
</tr>
<tr>
<td>2</td>
<td>K</td>
<td>2.0</td>
<td>23.05</td>
<td>1.06</td>
</tr>
<tr>
<td>3</td>
<td>L</td>
<td>2.5</td>
<td>23.05</td>
<td>1.32</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>1.6</td>
<td>23.05</td>
<td>0.84</td>
</tr>
<tr>
<td>5</td>
<td>N</td>
<td>2.0</td>
<td>27.21</td>
<td>1.06</td>
</tr>
<tr>
<td>6</td>
<td>O</td>
<td>2.5</td>
<td>23.05</td>
<td>1.32</td>
</tr>
<tr>
<td>7</td>
<td>P</td>
<td>1.6</td>
<td>23.05</td>
<td>0.84</td>
</tr>
<tr>
<td>8</td>
<td>Q</td>
<td>2.0</td>
<td>33.78</td>
<td>1.06</td>
</tr>
<tr>
<td>9</td>
<td>R</td>
<td>2.5</td>
<td>23.05</td>
<td>1.32</td>
</tr>
</tbody>
</table>

Specimen L was designed as a PCRC beam with cold formed steel sheet of thickness 2.5mm (Tensile reinforcement ratio of 1.32%). The compressive strength of specimen L is 23.05N/mm². Specimens O and R were designed with the same tensile reinforcement area as in specimen L. Only the compressive strength of the specimen O and R were increased to 27.21 N/mm² and 33.78 N/mm² respectively versus 23.05 N/mm² for specimen L.

Table 2 shows the material properties of the test specimens. The concrete strength of each specimen is determined in accordance with Indian standard code test method (IS 516). 6 cubes were cast for each mix and tested for the compressive strength on the day of testing the specimen. Tension tests on coupons cut from structural sheet sheets were performed to determine material properties such as yield strength and ultimate strength.

Table 2: Material properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Properties (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>fₖ₀</td>
</tr>
<tr>
<td>Mix ratio : 1:1.87:4.65  , W/C ratio : 0.50</td>
<td></td>
</tr>
<tr>
<td>Concrete (J,K,L)</td>
<td>23.05</td>
</tr>
<tr>
<td>Concrete (M,N,O)</td>
<td>27.21</td>
</tr>
<tr>
<td>Concrete (P,Q,R)</td>
<td>33.78</td>
</tr>
<tr>
<td>CR sheet (1.6mm)</td>
<td>-</td>
</tr>
<tr>
<td>CR sheet (2.0mm)</td>
<td>-</td>
</tr>
<tr>
<td>CR sheet (2.5mm)</td>
<td>-</td>
</tr>
</tbody>
</table>
2.2 Concreting and Test Procedures

The beams were cast in steel moulds and compacted by needle vibrator. Significant numbers of 150 mm size cubes and 150 x 300 mm size cylinders are cast from each batch to determine the properties of concrete. The beams and the control specimens were demoulded on the next day of casting and moist cured for 7 days by wrapping them with wet gunny sacks followed by a polyethylene sheet to prevent moisture loss. The beams were tested at an age of at least 28 days. The beams were suitably instrumented for measuring deflection, concrete strain at top surface and bottom strain and curvature over a central gauge length of 300 mm. All the beams were tested in 50T loading frame, using a hydraulic jack of capacity 30T under two concentrated loads placed symmetrically 1.04m apart. The test setup is shown in Figure 2. The tests are carried out to failure.

Figure 1. Cross sectional view of PCRC beam.

Figure 2. Test setup over strong floor.
3. TEST RESULTS AND DISCUSSION

3.1 Failure Pattern
All the beams exhibit a fairly ductile behaviour as shown in Figure 3. Its failure results from the yielding of PCS followed by the crushing of concrete. At about 40% of the ultimate load, fine flexural cracks appeared at the bottom of the specimen. With further increase in the load, regularly spaced vertical cracks were observed and they extended from the bottom of the specimen towards the top fibre. The failure occurs in the tensile zone following the appearance of one macrocrack in pure bending region. The load was increased upto ultimate stage. After the attainment of ultimate load, the load was maintained till failure due to the confinement effect provided by PCS.

3.2 Moment Curvature Curves
The set of Moment curvature curves does not show significant differences during the loading. The applied load upon the structure increases until failure. The first stage corresponds to the elastic behaviour without any cracks. In the second stage the cracking decreases the moment of inertia and therefore the bending stiffness of the beam. The last stage of the curves corresponds to the yielding of PCS. Typical moment – curvature curves and moment versus flexural rigidity (EI) for PCRC beams are shown in Figure 4. The experimental observations at different stages of loading are tabulated in Table 3.

(b) Moment-curvature plot for M, N, and O series

(c) Moment-curvature plot for P, Q, and R series

Figure 4. Moment-curvature plot of PCRC beams.
3.3 Load – Strain Response

The load - strain curves as indicated in Figure 5, illustrate the behaviour per unit length until the failure of concrete and steel. For L, O and R Series Beams the stress - strain response shows a strain hardening behaviour. This allows an increase in the moment supported by the beam.

(a) Load - response for J, K, and L series

(b) Load - response for M, N, and O series
4. EXPERIMENTAL OBSERVATIONS ON DUCTILITY

The ability of a member to deform without a significant loss of its strength is known as ductility. One method of quantifying ductility is by using the ductility factor (ductility index) as defined by the ratio of ultimate deflection to the deflection at yielding of tensile reinforcement. Ductility Index, based on the failure state, where the failure load may be considered as equal to 85% of the ultimate load in the descending part of the load-deflection curve, is also of interest in some cases, especially in seismic design.

The displacement and curvature ductility factors based on yielding of steel and ultimate stage are shown in Table 3. It can be seen that displacement ductility factor \( (\mu_\Delta) \) varied from 6.92 to 12.59 and curvature ductility factor \( (\mu_\phi) \) varied from 3.76 to 9.26 for PCRC Beams. For the redistribution of moments to be considered, a minimum ductility index \( \mu_\Delta \) of 3 is generally required[10]. Generally a beam without compression reinforcement is very poor in ductility whereas in PCS, the provision of compression steel in the form of horizontal strips coupled with stirrups in the form of vertical continuous strips substantially improves the ductility index. PCS has better confinement capacity than normal RCC beams preventing the disintegration of concrete in the compression zone even after the concrete cover has spalled off, thereby improving failure ductility. The vertical continuous strips in PCS, acting as closely spaced stirrups in the maximum bending moment region can substantially improve the failure ductility of PCRC beams.
Table 3: Experimental results

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Beam Id</th>
<th>Load, $P_s$ (kN)</th>
<th>Deflection, $\Delta_s$ (mm)</th>
<th>$P_y$ (kN)</th>
<th>$\Delta_y$ (mm)</th>
<th>$\phi_y$ (10^-3 per m)</th>
<th>$P_u$ (kN)</th>
<th>$\Delta_u$ (mm)</th>
<th>$\phi_u$ (10^-3 per m)</th>
<th>$\mu_s = \Delta_u/\Delta_y$</th>
<th>$\mu_u = \phi_u/\phi_y$</th>
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<tbody>
<tr>
<td>1</td>
<td>J</td>
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<td>27.5</td>
<td>5.40</td>
<td>16.02</td>
<td>37.75</td>
<td>68.00</td>
<td>118.13</td>
<td>12.59</td>
<td>7.37</td>
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<tr>
<td>2</td>
<td>K</td>
<td>28.33</td>
<td>4.16</td>
<td>35.00</td>
<td>6.91</td>
<td>27.50</td>
<td>42.50</td>
<td>63.27</td>
<td>162.59</td>
<td>9.16</td>
<td>5.91</td>
</tr>
<tr>
<td>3</td>
<td>L</td>
<td>35.83</td>
<td>5.40</td>
<td>37.50</td>
<td>8.00</td>
<td>31.33</td>
<td>53.75</td>
<td>61.65</td>
<td>124.84</td>
<td>7.70</td>
<td>3.98</td>
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<tr>
<td>4</td>
<td>M</td>
<td>27.17</td>
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<td>32.50</td>
<td>7.46</td>
<td>15.23</td>
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<td>77.25</td>
<td>141.02</td>
<td>10.36</td>
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<td>N</td>
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<td>44.25</td>
<td>72.36</td>
<td>142.19</td>
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<td>O</td>
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<td>5.66</td>
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<td>55.0</td>
<td>68.53</td>
<td>126.88</td>
<td>7.45</td>
<td>3.76</td>
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<td>P</td>
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<td>35.00</td>
<td>8.60</td>
<td>20.78</td>
<td>42.50</td>
<td>81.83</td>
<td>140.47</td>
<td>9.52</td>
<td>6.76</td>
</tr>
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<td>Q</td>
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<td>5.62</td>
<td>38.00</td>
<td>10.32</td>
<td>29.61</td>
<td>47.25</td>
<td>73.94</td>
<td>134.22</td>
<td>7.16</td>
<td>4.53</td>
</tr>
<tr>
<td>9</td>
<td>R</td>
<td>38.33</td>
<td>5.87</td>
<td>42.50</td>
<td>10.23</td>
<td>21.48</td>
<td>57.50</td>
<td>70.80</td>
<td>89.92</td>
<td>6.92</td>
<td>4.19</td>
</tr>
</tbody>
</table>

* Assumed service load is taken as ultimate load/1.5

4.1 Energy Absorption Capacity
Ductility can be quantitatively measured in terms of the energy absorption capacity [9]. Energy absorption capacity of the members can be approximated as the area enclosed by the load deflection curve. The ability of a structural member to absorb energy is an important factor in the overall performance of structural elements. At cracking, yielding of tension steel and at ultimate stage, PCRC beams exhibited a substantial increase in the energy absorption capabilities thereby indicating improved ductile characteristics.

5. CONCLUSIONS
The tests on beams carried out in this study describe the possibility of using Prefabricated Cage System for reinforcements. From the results of the experimental study reported herein, the following conclusions can be drawn.
- PCRC beams show more ductility due to the confinement of the compression zone. The displacement ductility factor varies from 12.59 – 6.92. The results reveal that cold-formed sheet of lesser thickness shows more ductile performance.
- The curvature ductility of PCRC beams varies from 9.26 – 3.76 for PCRC Beams. For the redistribution of moments to be considered, a minimum ductility index $\mu_A$ of 3 is generally required.
- The ability of a structural member to absorb energy is an important factor in the overall performance of structural elements. The test results reported herein is shown that PCS is...
very effective in energy absorption capabilities.

- The compressive strength of concrete appeared to have no significant effect on the strength and ductility of the PCRC beams.

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