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Abstract

The ductility of HSC beams is enhanced through the application of helical reinforcement located in the compression region of the beams. The diameter and pitch of helix are important parameters controlling the level of ductility enhancement of over reinforced high strength concrete beams. This paper presents an experimental investigation of the effect of helix pitch and diameter on the beam behaviour through testing 10 helically confined full scale beams. Two groups of five beams each had exactly the same geometry and reinforcement; with the only differences being the diameter and pitch of the helices. For one group the helix was made of 8 mm diameter bars and the second of 12 mm diameter bars. The helix pitches were 25, 50, 75, 100 and 160 mm. Beams’ cross section was 200×300 mm, with a length of 4 m and a clear span 3.6 m subjected to four point loading, with emphasis placed on the mid-span deflection. The main results indicate that the helical effectiveness is negligible when the helical pitch is 160 mm (helix diameter) and the displacement ductility index increases as the helical pitch decreases. Finally, considerable displacement ductility is revealed for beams confined with 25 mm pitch helix in both the 8 mm and 12 mm helix bar diameter.

Keywords: ductility; high strength concrete; reinforced concrete; helical reinforcement

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1.0 Introduction

The development of the construction industry have led to the continual improvement of construction materials. Where, high strength concrete of 100 MPa compressive strength and reinforcement of 500 MPa yield strength are used in beams and other construction elements. High strength concrete (HSC) could be used when the reduction in cross section of the member is required. The disadvantage of using HSC in over reinforced beam is its brittle failure. One option for changing the type of failure from brittle to ductile is through confining the compression region of the concrete. Helical reinforcement can be used to achieve the required ductility. It is generally accepted that helical confinement is more effective than the rectangular ties in increasing the strength and ductility of confined concrete. Helical reinforcement is effective for concrete under compression to increase the ductility as well as the compressive strength by resisting the lateral expansion due to Poisson’s effect upon loading. Herein the helical reinforcement is used in the compression zone of the beams. The effectiveness of the helical confinement depends on different important variables such as helical pitch and diameter of helix. This paper presents the experimental results of testing ten full-scale beams with 4000 mm length and a cross section of 200 mm in width and 300 mm in depth.

2.0 Experimental program

Shah and Rangan 1970 [1] proved experimentally that using helical confinement in the compression zone of rectangular beams is more effective than using rectangular ties with compression longitudinal reinforcement as such reinforcement tend to buckle pre-maturely. This study adopts the same concept. Sheikh and Uzumeri (1980) [2] examined the effect of different variables on the behaviour of strength and ductility of columns by testing 24 specimens. The results pointed out to the significant influence of the helical pitch on the behaviour of confined concrete. Shin et al. (1989) [3] tested 36 beams, four of which were to study the effect of tie spacing on ductility. The results did not show clearly the importance of confinement spacing. It may be because the spacings studied were only 75 and 150 mm which, did not provide adequate data to figure out the importance of confinement spacing. Hadi and Schmidt (2002) [4] tested seven HSC beams helically confined in the compression zone, all beams had the same helical pitch of 25 mm to study the influence of different variables excluding the helical pitch. However, the literature indicates the importance of helical pitch, but there is no quantitative data for over reinforced helically confined HSC beams.

The aim of the experimental program in this study is to investigate the behaviour of over-reinforced HSC helically confined beams and determine the effect of helix diameter and its pitch on ductility. Helical pitch and helix diameter were the parameters selected for investigation in this experimental program. In the test program reported herein, a total of ten beams were cast in two batches each batch had five different pitches, namely 25, 50, 75, 100 and 160 mm. The difference between the two batches was the helix diameter. All ten beams had the same dimensions; generic details of the beams are shown in Figure 1. Each beam was reinforced with 4N32 bars (32 mm deformed bars of 500 MPa tensile strength and of normal ductility). Stirrups of plain 10 mm diameter (250 MPa tensile strength) were provided at either third end of the beams at a spacing of 80 mm. Two 10 mm bars were installed at the top of the beams at either third in order to keep the ties in-place. For the first five beams the helix was made of 12 mm deformed bars and for the second five beams the helix was made of 8 mm
plain bars. Each group of five beams were cast at the same day using five wooden moulds. The beams were then cured by covering them with wet Hessian bags.

The concrete used in this experimental program was supplied as ready mix by a local supplier and was specified to gain 100 MPa for both batches. The concrete compressive strength of the first five beams was 105 MPa, and the concrete compressive strength of the second five beams was 80 MPa.

$S' = 25, 50, 75, 100$ and $160$ mm

Figure 1. Loading configuration and specimen details.
All beams were heavily instrumented. Reinforcement steel deformation was measured using electrical resistance strain gauges (10 mm length) glued to the steel bars at mid-span of the bar and 300 mm away from the mid-span in both sides of the bar. Also the strains of the helical reinforcement were measured using electrical resistance strain gauges (5 mm in length) glued at the bottom, top and sides of the helical reinforcement at the mid-span of the beam and 300 mm away from the mid-span of the beam. The strain on the compression zone of the beam was measured using two electrical resistance strain gauges (60 mm in length) glued on the top surface at mid-span of the beam. For each beam, two embedment gauges were placed at a depth of 40 mm, one at the beam’s mid-span and the other 300 mm away from the mid-span of the beam. The data recorded from the embedment gauges were used to calculate the strains at the top surface after spalling off the concrete cover.

The beams were tested under four-point loading regime in the strong floor of the civil engineering laboratory at the University of Wollongong. The displacement-controlled load was applied using 600 kN actuators. The mid-span deflection of the beam was measured using linear variable differential transformers (LVDTs).

3.0 Effect of helix pitch

From Figures 2 and 3 it could be noted the remarkable effect of helical pitch on mid-span deflection. Beams, which have helical pitches of 25, 50, 75 and 100 mm failed in a ductile manner. The level of the ductility depends on helical pitch. The Beam 12HP160 failed in a brittle mode, as the upper concrete in the compression zone was crushed and the maximum load was 413 kN and then dropped to 150 kN. Also the maximum load for Beam 8HP160 was 376 kN and then dropped to 94 kN. This drop indicates the effect of confinement is negligible when the spacing is equal to the confinement diameter, which is in agreement with the experimental results by Iyengar et al. (1970) [5] and Martinez et al. (1984) [6]. Figure 4 shows the relation between the helical pitch and ultimate mid-span deflection. Beams 12HP25 and 8HP25 showed a maximum deflection of 240 and 185 mm, respectively and the deflection is reduced as the pitch was increased.

Deflection ductility index is defined as the ratio of ultimate deflection to the yield deflection. Where the ultimate deflection refers to the arising of softening behaviour in the overall response of the beams. Figure 5 shows that the deflection ductility index (normalised ductility based on the ductility of the beam with helix pitch 160 mm) increases as the helical pitch decreases. It is to be noted that, there is no considerable difference between yield deflections for the ten beams compared to the ultimate deflection. Hence, it can be concluded that the deflection ductility index is affected significantly by the ultimate deflection. It could also be concluded that the helical pitch has a significant effect on the ultimate deflection but less significant effect on the yield deflection. It is to be noted that during the tests, the helices yielded after the yield of the longitudinal bars. Helical pitch is an important parameter in enhancing the ductility of beams.
**4.0 Influence of helix diameter**

It is difficult to find out the effect of helix diameter on the displacement ductility index ($\mu_d$) because of the concrete compressive strength was not the same for the two batches. However the effect of concrete compressive strength can be taken into account by dividing the reinforcement ratio $\rho$ by the maximum allowable tensile reinforcement ratio $\rho_{\text{max}}$ as specified by AS3600 (2001) [7], which is shown in equation 1. Figure 6 shows $\mu_d$ versus $\rho/\rho_{\text{max}}$.

$$\rho_{\text{max}} = \frac{0.34 \gamma f'_c}{f_{sy}} \tag{1}$$

$\gamma$ = ratio under design bending or combined bending and compression of the depth of assumed rectangular compressive stress block to $K_n d$.

$K_n$ = ratio of depth to neutral axis to the effective depth.

d = effective depth.

$f'_c$ = characteristic concrete compressive strength at 28 days, MPa.

$f_{sy}$ = yield strength of reinforcing steel, MPa.

![Figure 2. Load-deflection curves for beams with helix diameter 12 mm](image_url)
Figure 3. Load-deflection curves for beams with helix diameter 8 mm

Figure 4. Ultimate mid-span deflection versus helix pitch
Figure 5. Effect of helix pitch on normalised displacement ductility

\[ \rho = 1.55 \rho_{\text{max}} \] for the beams confined with helix diameter 12 mm and the concrete compressive strength 105 MPa, and for the beams confined with helix diameter 8 mm with concrete compressive strength of 80 MPa, \( \rho = 1.93 \rho_{\text{max}} \). From Figure 6 it is noted that the effect of helix diameter is negligible when the helix pitch was 25, 75 and 100 mm, but for beams with helix pitch 50 mm, the effect of helix diameter was significant. It could generally be concluded that the significant effect of helix diameter on the displacement ductility index of beam is more noticeable when the helix pitch is between 25 mm and 75 mm.

Figure 6. displacement ductility versus \( \rho/\rho_{\text{max}} \)
5.0 Influence of helix reinforcement ratio

Figure 7 shows the relation between the displacement ductility index versus the \((\rho f_{yh}/f_c)\) where \(f_{yh}\) is the helical steel strength; \(f\) is the concrete compressive strength and \(\rho\) is the volumetric helical reinforcement ratio expressed in equation 2.

\[
\rho_h = \frac{\pi d_h^2}{d_c s_h}
\]

Where \(\rho_h\) = volumetric helical reinforcement ratio
\(d_h\) = helix diameter
\(d_c\) = confined concrete core diameter
\(s_h\) = helical pitch

Volumetric helical reinforcement ratio is a function of helix diameter, helical pitch and confined concrete core diameter. It is difficult to find the exact effect of volumetric helical or tie reinforcement ratio for confined beams because the confinement is more effective when it is provided in the compression zone. Mansur et al. (1997) [8] and Ziara et al. (2000) [9] found that the mid-span displacement ductility of beams with short depth link is more than the mid-span ductility of beams with full depth link. From equation 2 the volumetric helical reinforcement ratio increases when the confined concrete core diameter decreases. As a result it is difficult to guarantee confining compression zone exactly in a beam and then the reinforcement volumetric lateral reinforcement ratio is not indicating the accurate value for the quantity required. However it could give a good indication of the volumetric helical reinforcement ratio for helically confined beams because the only way for placing the helix is in the top part of the beam (short depth link) and the concrete core diameter taken as the width of the beam subtracting the concrete cover at both sides.

In this experimental program the confined concrete core diameter was 160 mm, where the best fit linear regression curve is shown in Figure 7. From that curve it can be concluded that the brittle failure occurs when the \((\rho f_{yh}/f_c) < 0.088\). For beams with \((\rho f_{yh}/f_c) > 0.088\) the displacement ductility increases, therefore, ductility is influenced significantly by the volumetric helical reinforcement ratio. Also it is noted that the negligible gain in displacement ductility is when \((\rho f_{yh}/f_c) > 0.314\). Then the ductile beam has \((\rho f_{yh}/f_c)\) between 0.088 and 0.314. In other words it could change the beam failure from compression to ductile failure by providing suitable volumetric helical reinforcement ratio and helix steel strength in the compression zone of the beam with specified concrete compressive strength. In fact this concrete compressive strength is enhanced when the helix resists the concrete core from expansion. In other words, the helix role starts when the confined concrete strength is enhanced (confined concrete strength). The enhancement of confined concrete strength depends on many factors such as helix pitch and helix diameter. From equation 1 increasing concrete strength increases the maximum reinforcement ratio. As a result, the effective reinforcement ratio becomes below the maximum reinforcement ratio. Generally failure type changes from brittle to ductile by providing the helix in the compression zone of over reinforced HSC beams.
6.0 Conclusion

The experimental program in this study is to investigate and provide experimental evidence about the significant effect of helical pitch on the displacement ductility of helically confined HSC beam. Ten over reinforced HSC beams helically confined were tested. Conclusions can be drawn about the behaviour of these beams with different helical pitch of 25, 50, 75, 100 and 160 mm and different helix diameter 8 and 12 mm.

The two beams with helical pitch of 160 mm (equal to the core diameter of the beam) has shown to be very brittle in their failure, providing no plateau region in their load deflection curves. The concrete spalled off at the failure load. The conclusion drawn from testing these beams is that the confinement effect is negligible when the helical pitch is equal to or greater than the core diameter for helically confined beams.

The other beams with helical pitch of 25, 50, 75 and 100 mm have shown to be ductile and the level of ductility is based on the helical pitch. The helixes effectively confined the compressive region when the helical pitch was reduced. It is interesting to note that the displacement ductility index increases as the helical pitch decreases. In other words, displacement ductility index is inversely proportional with the helical pitch. The effect of helix diameter is negligible when the helix pitch is very small such as 25 mm also when the helix pitch is as large as 75 or 100 mm. However the significant effect of the helix diameter on the displacement ductility index is only when the helix pitch is between 25 mm and 75 mm.
There was no significant difference between the yield deflections of the beams but there was significant difference between the ultimate deflections for the ten beams. That is an indicator that the helix effectiveness takes place after yield deflections takes place and then the concrete strength is enhanced (confined concrete strength). The change of confined concrete strength depends on many factors such as helix pitch and helix diameter. As a result the failure type changes from brittle to ductile. Generally providing the helix in the compression zone of beams with a suitable helix pitch can enhance the ductility of over reinforced HSC beams reinforced with high strength steel.

7.0 References


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