ASIAN JOURNAL OF CIVIL ENGINEERING (BUILDING AND HOUSING) VOL. 11, NO. 4 (2010)
PAGES 451-462

EFFECT OF DIFFERENT CONFINEMENT SHAPES ON THE BEHAVIOUR OF REINFORCED HSC BEAMS

M. N. S. Hadi* and R. Jeffry
School of Civil, Mining and Enviornomental Engineering, University of Wollongong, Wollongong, Australia

ABSTRACT

High strength concrete (HSC) provides high strength but lower ductility compared to normal strength concrete. This low ductility limits the benefit of using HSC in building safe structures. This means that a designer should be aware of limiting the amount of tensile reinforcement to prevent the brittle failure of concrete. Therefore the full potential of the use of steel reinforcement cannot be achieved. This paper presents a method to prevent the brittle failure of concrete beams. Five beams made of HSC were cast and tested. The cross section of the beams was 200×300 mm, with a length of 4 m and a clear span of 3.6 m subjected to four-point loading, with emphasis placed on the midspan deflection. The first beam served as a reference beam. The remaining beams had different tensile reinforcement and the confinement shapes were changed to gauge their effectiveness in improving the strength and ductility of the beams. The compressive strength of the concrete was 85 MPa and the tensile strength of the steel was 500 MPa and for the stirrups was 250 MPa. Results of testing the five beams proved that placing helixes with the right diameter and pitch in the compression zone of reinforced concrete beams improve their strength and ductility.

Keywords: Helical reinforcement; ductility; confinement; high strength concrete; beam

1. INTRODUCTION

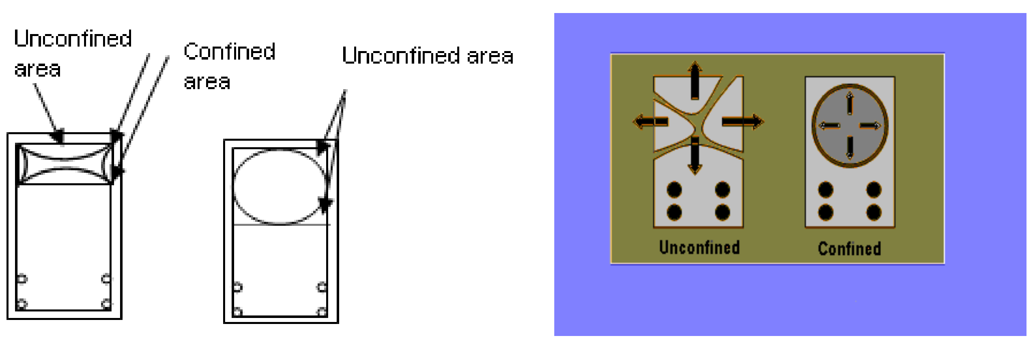
The use of high strength concrete is increasing rapidly in most of construction projects around the world especially in high rise buildings. This increase is because HSC has an advantage which enables a reduction in the cross section and thus weight of construction members. This reduction in cross-section and dead load leads to greater floor space in the case of high rise buildings and reduces construction costs. High strength concrete is inherently more brittle than normal strength concrete. As the strength and therefore brittleness of concrete increases the ductility of the concrete will decrease. It is important to design structures to fail in a ductile manner to allow for deflections and other warning signs to show before complete failure occurs. The reduction in ductility can lead to catastrophic

* E-mail address of the corresponding author: mhadi@uow.edu.au (M. Hadi)

failure of structural members, which then could lead to loss of human lives. The Australian Standards AS3600 [1] cover concrete up to a characteristic compressive strength of 65 MPa. Although with careful design and use of high quality materials high strength concrete can reach strengths well in excess of 120 MPa. Studies into developing design charts for the flexural ductility of high strength concrete beams have been conducted to try and allow for greater ease to design concrete structures with these increased high strengths. This paper investigates the increase in ductility of high strength concrete beams through the use of different shapes of confinement reinforcement. Reinforcement in the compressive zone increases the compressive capabilities of the concrete thus allowing the steel within the concrete to yield first producing a ductile failure.

2. CONFINEMENT BEHAVIOUR AND MECHANISM

Helical confinement is more effective than rectangular ties in increasing the strength and ductility of confined concrete. The reason behind this is a helix applies a uniform radial stress along the concrete member, whereas a rectangle tends to confine the concrete, mainly at the corners. Figure 1(a) shows a comparison between helix and tie confinement. The confining reinforcement increases ductility and compressive strength of concrete under compression by resisting lateral expansion due to Poisson's effect upon loading. The behaviour of confined concrete depends on the effectiveness of the confinement, which in turn is affected by several important variables such as helical pitch, helix yield strength and helix bar diameter. When a helically confined beam is loaded, the stresses in the helices will be negligible. As the load increases the stresses within the helix increase and due to Poisson's effect the confining stresses will increase and thus confinement will commence. Confinement does not increase strength or ductility initially, but when the axial stress is about 60% of the maximum cylinder strength, the concrete is effectively confined [2]. Figure 1(b) shows the differences between confined and unconfined reinforced beam.



Beam confined by rectangular tie

Beam confined by Helix

(a) Confined and unconfined compression area in concrete beams

(b) Effect of helical reinforcement in beams compressive region

Figure 1. Confind concrete beams

3. REVIEW OF LITERATURE

The brittleness of high strength concrete is significant when used in concrete structures, in other words using high strength concrete without preventing the brittle failure is risky and unacceptable. Ductility is an important factor as it ensures large deformation to occur under overload conditions and high ductility enables a concrete segment or a joint to sustain plastic deformations without reduction in stress. Large deflections in structures provide a good warning of failure in the form of tensile cracks prior to complete failure of the beam. Most of the studies concerning confinement of the compression zone in beams is based on the results of research on columns, because the idea of a confined compression zone in beams has only been developed recently. Having said that, the literature and data available about columns confinement is more than for beam confinement. It was first observed by Ritchart et al. [3] that confined concrete from the surrounding steel sections showed great increase in the maximum compressive strength, stiffness, and extended strain at which the peak stress was reached. When the concrete experiences deformation, there is no substantial reduction of the load bearing capacity and it fails gradually in a ductile way. Hatanaka and Tanigawa [4] stated that, beams confined by helix produce a lateral pressure more than beams confined by rectangular tie, in other words, rectangular tie is about 30 to 50 percent of the pressure introduced by a helix. This statement supports the output of the experimental research conducted by Chan [5], who showed that the efficiency of tie confinement is 50% of the helical confinement for the same lateral reinforcement ratio. The effectiveness of helix applies to concrete in compression for both beams and columns. The reason why a helix is more effective than a tie is because it applies a uniform radial stress along the concrete member, whereas a rectangle tends to confine the concrete, mainly at the corners. Martinez et al. [6] investigated the difference in behaviour between spirally confined NSC and HSC column. They tested 94 small diameter columns, which were divided into four groups, The first group specimens had 102 mm diameter by 203 mm high, The second group specimens had 102 mm diameter by 406 mm high, the third group specimen had 127 mm diameter by 610 mm high and the fourth group specimens had 152 mm diameter by 610 mm height. The concrete compressive strength used varied between 21 to 69 MPa and no longitudinal reinforcement was included. The first 78 columns had no protective concrete cover over the spiral steel while the rest (16 columns) had concrete cover over the spiral steel. They measured the strains and the total axial deformation in the lateral steel. Based on these experimental results Martinez et al. [6] proposed an equation for predicting the confined strength of HSC and NSC

$$f_{cc} = 0.85\, f_c^{'} + 4.0\, f_2 \left(1 - \frac{s}{d_c}\right) \tag{1}$$

Where:

f'_c= Compressive strength of concrete (MPa)

f_2 = lateral pressure (MPa)

s = pitch of helical reinforcement (mm)

d_c= outside diameter of confined concrete (mm)

In addition they concluded from their experimental investigation, in case of using helical steel with yield stress exceeding 414 MPa will probably result in unconservative design if the steel used based on assumption at yield point at the computed failure load of the column. In regard to modulus of elasticity they concluded that, there is no difference between the confined and unconfined concrete of these spirally confined columns. Finally, they concluded that, if the helical pitch was equal to the confinement diameter then the effect of confinement is negligible. Kwan et al. [7] tested 20 reinforced concrete beams and they stated that to avoid brittle failure and ensure minimum ductility, it is proposed to set a maximum limit to the tension steel to balanced steel ratio. The values of the proposed maximum limit, which gradually decreased as the concrete strength increased to account for the lower ductility of higher strength concrete, since the balanced steel ratio increases with the concrete strength, the maximum allowable tension ratio still increases with the concrete strength equal to 80 MPa. Thus, the use of HSC in place of normal strength concrete does allow the bending strength of the beam to be increased while maintaining a similar ductility. However, the net increase in bending strength due to use of high strength concrete is relatively small compared to the increase in concrete strength. Finally, Kwan et al. [7] concluded that, the ductility for reinforced concrete beam using HSC with compressive strength greater than 80 MPa needs to be significantly improved.

Hadi and Schmidt [8] tested seven beams with a cross section of 200 $\times$ 300 mm^2 by 4060 mm long with a clear span of 3700 mm. The concrete cover was 20 mm. The main objective of this study was to investigate the beams' ductility when helical reinforcement in the compression region was applied. From their study, Hadi and Schmidt [8] concluded that the beam without helix was very brittle in its failure, while the beam with helix continued to deflect for a longer time. The conclusion they came out with was, if the correct pitch is utilised for effective confinement, helical reinforcement will provide an economical solution for enhancing the strength of flexural members [8].

Whitehead and Ibell [9] tested seven rectangular steel reinforced beams. Each helically reinforced specimen contained a single helix with a 20 mm pitch. The helices were formed from either 3 mm or 4.8 mm diameter mild steel wire. To show the full benefit of the presence of a circular helix, control specimen (no helix) and specimens containing a similar volume by weight of rectangular links were tested for direct comparison purposes. They came out with conclusion of, placing a steel helix (of 3 mm or 4.8 mm diameter wire) in the compression zone of a heavily over reinforced (with steel reinforcement bars) concrete beam, considerable ductility has been achieved, even using a longitudinal steel percentage of about 7%. This finding is considered exciting in an attempt to achieve shallower concrete structures that are heavily over-reinforced, but which are nonetheless ductile. Ross and Hadi [10] investigated five beams of 4000 mm length and a cross section of 200 mm in width and 300 mm in depth and a clear span of 3600 mm subjected to four point loading, with emphasis placed on the midspan deflection. The variables such as concrete compressive strength and longitudinal reinforcement ratio, helix pitch have been kept same, and the only parameters changed were the helical helix diameter and stirrups spacing at the mid part of the beam. The helix pitch was 50 mm and the stirrups spacing was varying from 50 mm to 100 mm. The output of this experimental program indicate that the helix diameter had diameter had significant effect when the helical pitch was 160 mm, in other words the behaviour of the beam was shown to be ductile in its failure, providing and the level of ductility based on helix diameter and stirrups spacing at the mid span. From what [10] achieved there is a need of investigating the effect of helix diameter and stirrups spacing at midspan as a combination variable parameters compared with different shapes and to investigate the effect of these parameters on neutral axis depth at the post-peak stage on flexural strength and ductility.

4. EXPERIMENTAL PROGRAM

Five beams have been designed, constructed, and tested according to AS3600 [1], in order to examine the effect of different types of confinement at the compression zone of each beam. Out of the five beams the first beam is the reference beam while the other four were designed with different arrangements of confining reinforcement promoting ductile failure to determine the effectiveness of the confining reinforcement in the compressive region of the beams. All five beams were over-reinforced for brittle failure in accordance with AS 3600 [1]. Table 1 shows details of each beam. All beams have the same dimensions 4000 mm (length), 300 mm (height) and 200 mm (width), with a concrete compressive strength of 85 MPa (at the time the beams were tested). The beams were classified as a reference beam as shown in Figure 2, Beam HTS as shown in Figure 3 (horizontal ties with stirrups along the beam with 50 mm spacing), Beam VTS as shown in Figure 3 (vertical ties and stirrups along the beam at 50 mm spacing), Beam DHS as shown Figure 4 (double helix with stirrups at midspan at 100 mm spacing) and finally Beam SHS as shown Figure 4 (single helix with stirrups along the beam at 100 mm spacing at midspan). All these beams have different forms of reinforcing confinement in the compression zone.

Table 1: Details of steel reinforcement and helix dimensions of the tested beams

Beam	**Length (mm)**	**Tensile reinforcement**	**Stirrups**				**Confining reinforcing**	
		Number of bars	**Diameter (mm)**	**Pitch at ends (mm)**	**Pitch at middle (mm)**	**Configured stirrups (mm)**	**Helix diameter (mm)**	**Pitch (mm)**
Ref	4000	4N28	10	50	50	None	None	
SHS	4000	2N24 + 2N32	10	50	100	None	160 ø	50
HTS	4000	2N24 + 2N32	10	50	50	2x(63x160)	None	
DHS	4000	2N24 + 2N32	10	50	100	None	2x80 ø	50
VTS	4000	2N24 + 2N32	10	50	50	2x(126x80)	None	

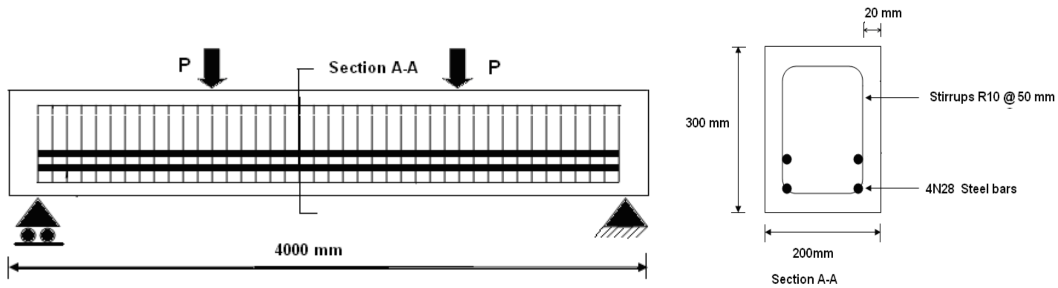
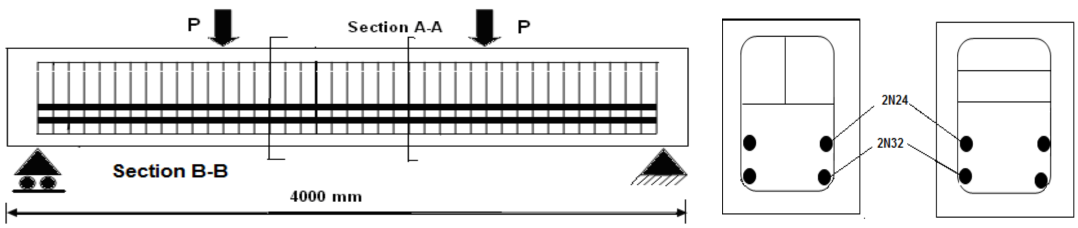


Figure 2. Details of the reference beam



Section A-A   Section B-B

Figure 3. Details of beams VTS and HTS

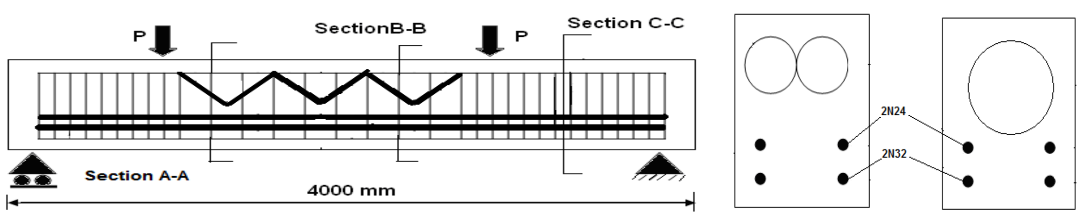


Figure 4. Details of beams SHS and DHS

5. ANALYSIS OF THE RESULTS

All beams were tested in the high bay laboratory at the University of Wollongong. Four point loading was used to test the beams. The applied load was displacement controlled. The applied load together with the corresponding mid-span deflection were recorded.

Figure 5 shows the load midspan deflection of all tested beam specimens. It can be noticed that, the beams' behaviour can be classified in two stages, the first stage is the elastic range up to the yield load and the second stage is the post yield. The post yield behaviour of each beam reflects the area ductility ratio as it gives an indication into the potential ductility of a beam. The graph also displays similarities between two sets of beams. It can be seen that the type of reinforcement is not the main governing factor of the beams' ductility and that the area of confined concrete can be seen to have a greater impact on the effect of the beams' ductility. Beams SHS and HTS display similar trends, although Beam SHS is the most efficient beam having the longer post yield plateau. Beam SHS, with the single helix and Beam HTS, with horizontal twin stirrups, both have close values of confined areas of concrete compared to each other. Beams DHS and VTS also display similar curves. Beam DHS, the double helical beam and beam VTS, with vertical twin stirrups also relate closely in confined concrete area. It is therefore taken that the area of confined concrete and not the type or arrangement of the confining reinforcement can enhance the ductility of a confined beam.

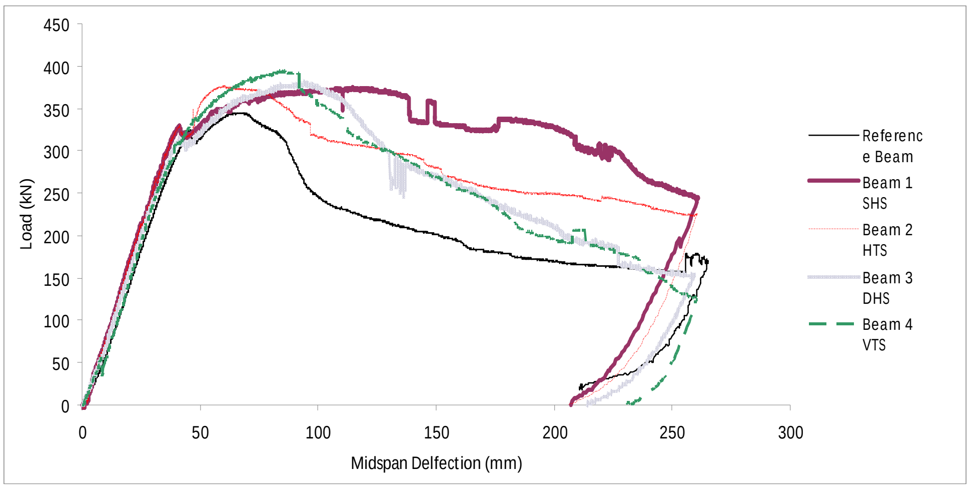


Figure 5. Load vs mid-span deflection for all five beams

Table 2: Ductility deflection index

Beam	**Yield load (kN)**	**80% of ultimate load (kN)**	**Deflection at yield load, Δ_y (mm)**	**Deflection at 80% of ultimate load, Δ_u (mm)**	**Ductility index (Δ_u/ Δ_y)**
Reference	325	260	35	95	2.71
SHS	330	264	32	240	7.5
HTS	360	288	34	144	4.23
DHS	310	248	31	168	5.42
VTS	310	248	31	156	5

5.1 Ductility

There are several methods to measure ductility of beams. One such method is ductility index. Table 2 shows the ductility index which is calculated by dividing the deflection at yield load 80% by the deflection at the ultimate load. Table 2 shows that Beam SHS had the largest ductility followed by Beams DHS, VTS, HTS and the reference beam.

After calculating the construction cost of each beam, Figure 6 shows the cost of all beams, it can be noticed that the highest total cost were Beams HTS and VTS. The reason behind this high cost is the two square shapes made for these beams was $569.

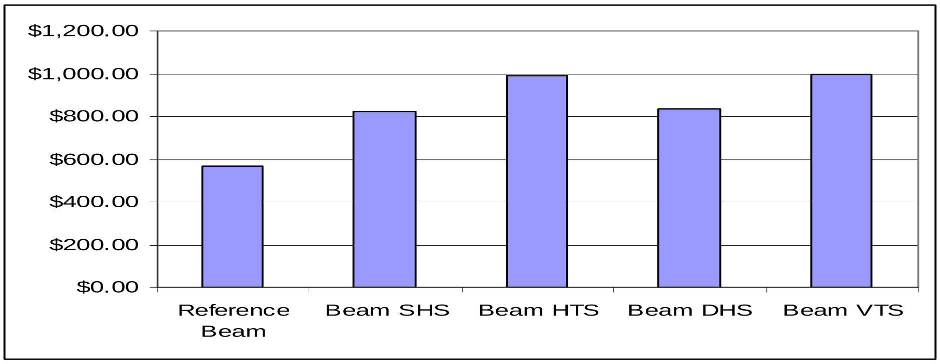


Figure 6. Beam cost comparison

Figure 7 shows the normalised ductility and strength of each beam against the normalised beam cost in order to find which beam is the most cost-effective. It can be noticed that Beam SHS was the most ductile beam for its cost, followed by Beam DHS. In terms of strength, the yield load of Beams DHS and VTS was greater than Beams SHS and HTS. This increase is due to the fact that by using double helix and vertical twin in Beams DHS and HTS increase the overall cost of these beams, on the other hand, the strength per dollar cost for these beams (VTS and HTS) were cost effective beams, and this can be noticed in Figure 8 which shows the yield load per cost of all tested beams.

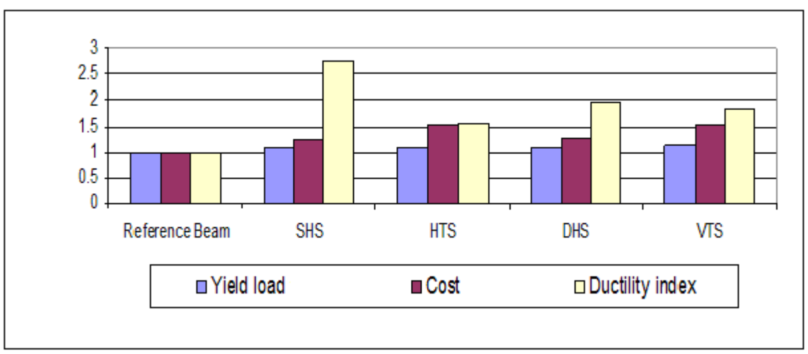


Figure 7. Normalized beam cost versus ductility and strength

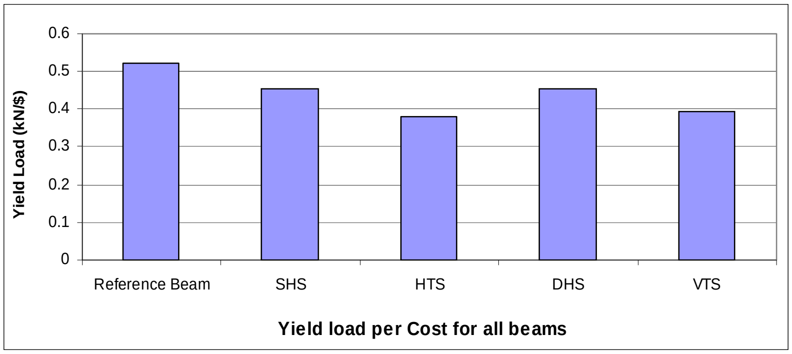


Figure 8. Yield load per cost of each beam

5.2 Further Cost Effectiveness analysis

A comparison between two high strength concrete beams and a theoretical normal strength concrete beam is presented in Table 3. Beams SHS and DHS were chosen as beam SHS had the best ductile properties, and Beam DHS was the most load efficient beam along with beam SHS. Beam A was designed with a ku value of 0.4 to ensure ductility and the required depth of the beam calculated as a result of the 375kN load of the beam to compare with beams SHS and DHS.

Table 3 shows that a significant increase in depth of a normal strength concrete beam is needed to produce the same properties as a high strength concrete beam. This is a major reason as to why the inclusion of provisions of high strength concrete in design codes is needed to optimize floor space in multi-story buildings. The increase in floor space and therefore increase in money to the developer is impacted by the extra costs associated with the load efficiency. To use high strength concrete, confining steel is required and thus increases the cost of steel with the high strength concrete also creating higher costs itself to be produced and purchased. Table 4 shows the load efficiency of beam A compared to Beams SHS and DHS from the previous table. The cost of the normal strength concrete was taken as $\$160/m^3$ and the labour cost of the beam was $100.

Table 3: Comparison between high strength and normal strength concrete beams

Property	Beam SHS	Beam DHS	Beam A
f'c (MPa)	85	85	32
fsy (MPa)	500	500	500
b (mm)	200	200	200
D (mm)	300	300	405
Ast (mm^2)	2512	2512	1445
Mu (kNm)	244	247	244
Pu (kN)	375	380	375

Table 4: Comparison of normal and high strength concrete load efficiency

Beam properties	Beam SHS	Beam DHS	Beam A
Depth of beam (mm)	300	300	405
Load efficiency (kN/$)	0.46	0.46	0.92

6. DISCUSSION

The aim of this experimental program was to improve the ductility of high strength concrete by using helices in the compression area of the beam, in other words, by confining the compression area with the use of these helices. In terms of ductility, the load midspan deflection behaviour of the beams in the elastic region are all very similar with the double helix beams and Beam VTS reaching a higher strength than the rest of the beams as the twin helices allowed an earlier confinement of the concrete in the compression zone. Beam SHS was the most ductile beam followed by Beam DHS and that is due to the fact that the helical reinforcement with stirrups acted as a confining mechanism for the concrete in the compression area, traixially stressing the concrete and improving the strength and strain capacity of the concrete. This failure occurred due to the fact that the neutral axis was not deep enough to enable adequate concrete to be in compression, and hence be in confined compression to take full advantage of the confining reinforcement available. The failure enabled the confining reinforcement to act more significantly due to the movement of the neutral axis. The cover spalling off reduced the effective depth and cross sectional area of the concrete, forcing an immediate drop in the depth of the neutral axis. This drop in the neutral axis engages a larger percentage of the concrete in the helical reinforcement to be in compression and as a result in a confined state. As stated above Beams DHS and VTS had the greatest ultimate loads and the helical beams were cheaper to construct than the configured stirrups resulting in Beam DHS having the best load efficiency. The load efficiency and cost effectiveness of using high strength concrete beams was considered in relation to normal strength concrete. Beam HTS, gives insight into the effect of confining area of concrete with the similarities between Beam HTS with Beam SHS. The higher ultimate load achieved by Beams DHS and VTS indicates that there was a larger area of concrete in confinement at the earlier stages of loading compared to the single helix and the reference beam, which allows for a greater ultimate strength being reached, they reached approximately 7% more than the other beams. From the load deflection curves of all beams, the beams behaved in a ductile manner, and ductility has presented due to the fact that the gradual decrease in capacity after initial failure does not continue, instead turns around and increases

The helices effectively confined the compression region of the beams allowing greater loads to be held after the initial spalling of the unconfined concrete. The neutral axis depths were well predicted in this experimental program. After spalling of the concrete had occurred to the outermost fibre, there would be a significant neutral axis shift due to the cross section of the beam reducing in size. This change of neutral axis location was taken into consideration in the theoretical calculations and predicted results were relatively close to the experimental results.

The impending demand of high strength materials to be used in the construction of beam members currently cannot be fully utilised, as both materials suffer from limited ductility. This deficiency in ductility reduces the ability to take full advantage of the increase in strength of both materials. Using steel helices to encase the concrete in the compression region of the beams increases their performances dramatically as revealed in this experimental program. Beam SHS was the most ductile beam for its cost, followed by Beam DHS. In terms of strength, the yield loads of Beams DHS and VTS were greater than Beams SHS and HTS this is due to the fact that Beams DHS and VTS included double helices. Finally, it can be concluded that installing helices in the compression zone of beams increases their strength and ductility.

7. CONCLUSIONS

Based on this study, the following conclusions can be made:

- The reduced ductility, due to the increase in tensile steel and the use of high strength concrete was overcome through the use of helical reinforcement in the compression region of the beam.
- The use of helical reinforcement was effective due to the lateral confinement of the concrete.
- The results from this study are encouraging and show the strength and ductility of over-reinforced beams can be increased by using helical reinforcement.

REFERENCES

1. AS3600, Australian Standard for Concrete Structures, Standards Association of Australia, North Sydney, 2001.
2. Sargin M. Stress-Strain Relationships for Concrete and the Analysis of Structural Concrete Sections. Solid Mechanics Division Study, University of Waterloo, No. 4, 1971, 167pp.
3. Richart FE, Brandtzaeg A, Brown RL. A Study of the Failure of Concrete Under Combined Compressive Stresses. University of Illinois Engineering Experimental Station, Bulletin, No. 185, 1928, 104 pp.
4. Hatanaka S, Tanigawa Y. Lateral pressure requirements for compressive concrete, *Proceedings of 10th World Conference on Earthquake Engineering*, Madrid, 1992, pp. 2603-2608.
5. Chan WWL. High-strength concrete: The Hong Kong experience, *Magazine of Concrete Research*, No. 21, **7**(1955) 121-32.
6. Martinez S, Nilson AH, Slate FO. Spirally reinforced high-strength concrete columns, *ACI Structural Journal*, No. 5, **81**(1984) 431-42.

7. Kwan A, Ho J, Pam H. Effect of concrete grade and steel yield strength on flexural ductility of reinforced concrete beams, *Australian Journal of Structural Engineering*, No. 2, **5**(2004) 119-38.
8. Hadi MNS, Schmidt LC. Use of helixes in reinforced concrete beams, *ACI Structural Journal*, No. 2, **99**(2002) 191-98.
9. Whitehead PA, Ibell TJ. Deformability and ductility in over-reinforced concrete structures, *Magazine of Concrete Research*, No. 3, **56**(2004) 167-77.
10. Ross J, Hadi MNS. Effect of confinement shapes on over-reinforced HSC Beams, *Proceedings of World Academy of Science*, *Engineering and Technology*, Paris, France, 2008, pp. 268-293.