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Displacement Ductility of Helically Confined HSC Beams

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Abstract: This paper presents an experimental investigation of the effect of helix pitch and helix diameter on beam behaviour through testing 10 helically confined beams. Two groups of beams had exactly the same geometry and reinforcement; with the only differences being the helices diameter and pitch. 8 mm helix was used in the first group of beams and 12 mm bars in the second group. The helix pitches varied between 25 mm and 160 mm. Beams' cross section was 200 × 300 mm, with a length of 4 m subjected to four point loading. The main results indicate that the helical effectiveness is neglected when the helical pitch is 160 mm (helix diameter) and the displacement ductility index increases as the helical pitch decreases. Finally, there is a considerable release of strain energy responsible for spalling off the cover.

Keywords: Ductility, high strength concrete, reinforced concrete, helical reinforcement.

1. INTRODUCTION

The development of the construction industry has 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 being used in beams and other construction elements. High strength concrete (HSC) is used when the reduction in member cross section is required. The disadvantage of using HSC in over reinforced beams 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 variables such as helical pitch. This paper presents the experimental results of testing ten beams with 4000 mm length and a cross section of 200 mm in width and 300 mm in depth.

2. COMPARISON BETWEEN HELIX AND TIE CONFINEMENT

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. Hatanaka and Tanigawa [1] stated that the lateral pressure produced by a rectangular tie is about 30 to 50 percent of the pressure introduced by a helix. That was in agreement with the experimental research conducted by Chan [2] who found that the efficiency of tie confinement is 50% of the helical confinement for the same lateral reinforcement ratio. The same effectiveness of confinement is applicable in columns and beams. Helix confines the concrete more effectively than rectangular ties as the helix applies a uniform radial stress on the concrete along the concrete member, whereas a rectangular tie tends to confine the concrete mainly at the corners. Thus the effective concrete area at the cross section is reduced because the concrete pressure will tend to bend the tie sides outward due to their low stiffness compared to the four corners [3]. As such a significant portion of the concrete in the cross section is considered as unconfined. On the other hand the arching of the concrete between the ties reduces the effective confined concrete at the cross section of the member. Thus using helical confinement in the compression zone of rectangular beams is more effective than using rectangular ties. Nevertheless, to prove experimentally that the helix is more effective than the rectangular ties, there is a need to compare beams helically confined with beams confined using rectangular ties. A study by Whitehead and Ibell [4] proved that the use of helical confinement is more effective than rectangular ties in beams.

3. THE EFFICIENCY OF HELICAL CONFINEMENT

Brittle failure (compression failure) could be prevented when the beam is designed as an under reinforced section as recommended by the codes of practice. However, providing longitudinal reinforcement ratio greater than the maximum recommended longitudinal reinforcement ratio increases the flexural capacity of the beam and at the same time will lead to brittle failure (non ductile failure). As such using reinforcement higher than the maximum is not recommended by the codes provision as ductility is an important factor related to human safety. Kwan *et al.* [5] found that the use of a higher steel yield strength as longitudinal reinforcement enhances the flexural strength of the beam section, but the flexural ductility is reduced. On the other hand the use of a higher steel yield strength as compression reinforcement might not have much beneficial effect on the flexural strength of the beam section, but the flexural ductility is

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enhanced. However, the most important issue is enhancing the concrete strength as well as its ductility.

There are different ways of improving the ductility of concrete in compression such as providing longitudinal compression reinforcement, by using randomly oriented steel fibres, or by installing helical or tie confinement in the compression zone. Comparison between those different methods to find the most effective method to enhance the strength and ductility of beams is presented below. Shah and Rangan [6] tested 24 groups of beams for comparison of ductility. The test was designed to be under four point loading to ensure failure in the central constant moment zone. This central zone contained closed stirrups of varying volumes, steel fibres of different amounts or compression longitudinal reinforcement of different volumes. The test results showed that the ductility of beam confined using tie confinement was 10 times the ductility of the control beams (without any ductility reinforcement), while the fibres increased ductility 4.5 times and compression steel increased ductility twice the control beams. This result shows that the tie confinement is more effective than the compression longitudinal reinforcement and steel fibre for enhancing the ductility. Also the beams, which have longitudinal compression reinforcement, suffer from early failure because of the compression reinforcing buckling problem. Furthermore Mansur *et al.* [7] and Ziara *et al.* [8] found that the mid-span displacement ductility of beams enhanced significantly by using rectangular tie confinement. As a result of the experimental program conducted by Shah and Rangan [6], which proved that providing confinement in the compression zone of the beam is more efficient than providing steel fibres or compression longitudinal reinforcement. Also most of the literature, such as Park and Paulay [3], Sheikh and Uzumeri [9], Hatanaka and Tanigawa [1] and Cusson and Paultre [10] prove that the helical confinement is more effective than rectangular tie confinement. In addition the efficiency of helical confinement was recognized by several building codes such as [11, 12]. However since 1971, ACI-318 [12] use an equation for calculating the rectangular confinement required which is derived based on the efficiency of rectangular confinement is 50% of the helical confinement.

4. EXPERIMENTAL PROGRAM

The main concept of this study is to encase the concrete in the compression zone by installing helical confinement in the compression zone. The helix will confine the concrete, and as well as improving its strength, it will enhance its ductility and prevent brittle failure.

A previous model test program was carried by Hadi and Schmidt [13], wherein a total of seven beams were cast and tested. The results of testing these beams were encouraging; these form the basis of this study to focus on the effect of helical pitch on over reinforced helically confined HSC beams. The experimental program presented in this paper is part of an on going research to study the behaviour of over reinforced helically confined HSC beams. See for example Elbasha and Hadi [14].

Sheikh and Uzumeri [9] examined the effect of different variables on the strength and ductility of columns by testing 24 specimens. The results pointed to the significant influence of the helical pitch on the behaviour of confined concrete. Shin *et al*. [15] tested 36 beams, four of which were to study the effect of tie spacing on ductility. The results did not clearly show the importance of confinement spacing. It may be because the spacings studied were only 75 mm and 150 mm, which did not provide adequate data to determine the importance of confinement spacing. Hadi and Schmidt [13] tested six beams helically confined in the compression zone and the seventh beam as unconfined beam (with no helix). The six beams had the same helical pitch of 25 mm to study the influence of different variables excluding the helical pitch. However, the literature indicate 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 pitch on ductility. In the test program reported herein, a total of ten beams were cast in two batches, each batch had five different helical pitches, namely 25, 50, 75, 100 and 160 mm. The helical pitch 160 mm chosen to verify if the effect of confinement is negligible when the helical pitch is equal to the confinement core diameter. This is based on the experimental results conducted by Iyengar *et al*. [16] and Martinez *et al*. [17]. Iyengar *et al.* [16] and Martinez *et al.* [17] found that the helical confinement has negligible effect when the helical pitch is equal to the diameter of confined concrete core. Based on these findings, this study did not include testing a control beam with no helical confinement. In addition, Hadi and Schmidt [13] include the testing of unconfined control beam (with no helix) as a basis for comparison with helically confined concrete beams. The behaviour of the control beam was shown to be very brittle in its failure, providing no plateau region in its load-deflection curve.

All ten beams had the same dimensions; generic details of the beams are shown in Fig. (**1**). Each beam was rein-

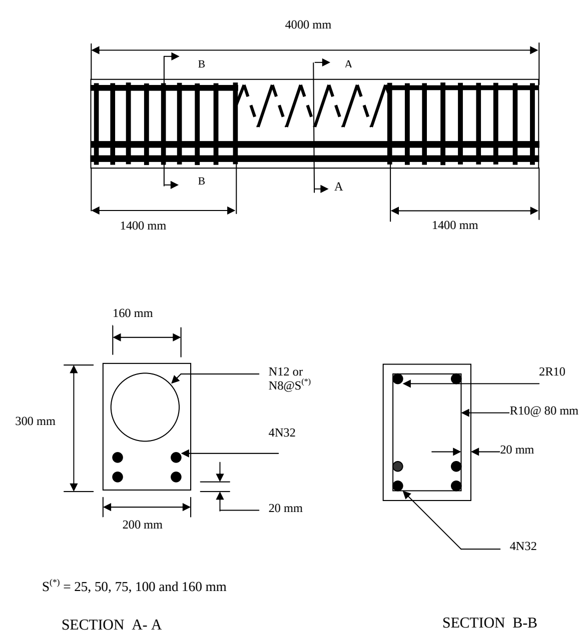

Fig. (1). loading configuration and specimen details.

forced 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 plain 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 plain 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 alphanumeric characters in the titles of the beams (e.g. 12HP25) have the following meaning: the first number presents the diameter of the helical steel. The two letters after the first number indicate that the only variable is the helical pitch. The second number refers to the helical pitch in mm.

4.1. Materials

The helical reinforcement was made of 8 mm and 12 mm diameter plain bars with 500 MPa yield strength. Each beam had four longitudinal deformed steel bars of 32 mm diameter and 500 MPa tensile strength. Figs. (**2**, **3**) and (**4**) show the stress-strain curves of the tensile strength tests of the 8 mm and 12 mm helix and the longitudinal reinforcing bars. The concrete used in this experimental program was supplied by a local ready mix supplier. The concrete compressive strength of the first five beams was 105 MPa at the time of testing, and the concrete compressive strength of the second five beams was 80 MPa at the time of testing.

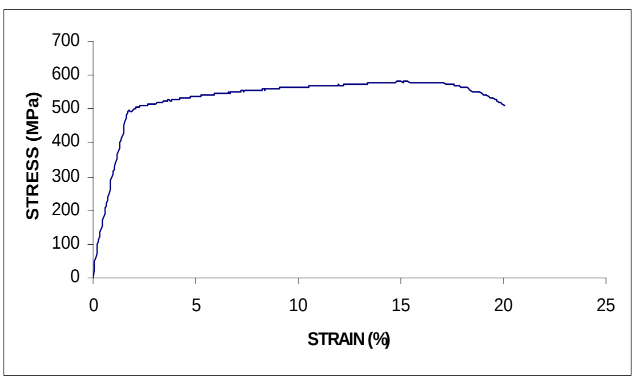

Fig. (2). Tensile stress strain curve for helical steel with 8 mm diameter.

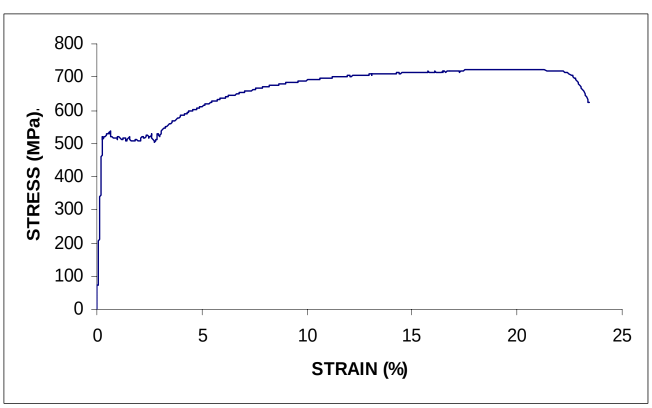

Fig. (3). Tensile stress strain curve for helical steel with 12 mm diameter.

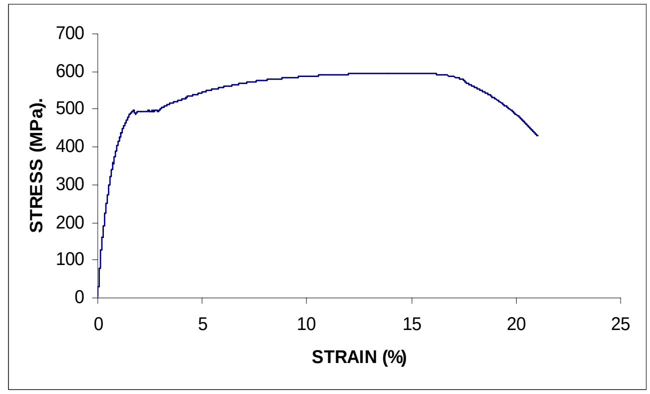

Fig. (4). Tensile stress- strain curve for longitudinal steel with 32 mm diameter.

4.2. Instrumentation

All beams were heavily instrumented. The deformation in the reinforcement bars was measured using electrical – resistance strain gauges (10 mm length) glued to the steel bars at mid-span of the beam 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) 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 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 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 a 600 kN actuator. The mid span deflection of the beam was measured using linear variable differential transformers (LVDTs). The LVDT was fixed to a U shaped steel plate attached at the bottom of the beams. This mechanism was used in order to prevent damage of the (LVDTs) when concrete cover starts spalling off.

Five different measurements were taken at each load increment: the strain at the top surface of the concrete, the concrete strain at 40 mm depth (using the embedment gauges), the strains in the longitudinal reinforcement, the strains in the helical reinforcement and the mid-span deflection. During testing, all data were recorded using Smart System installed on a PC computer.

5. ANALYSIS OF TEST RESULTS

A summary of the test results is presented in Tables **1** and **2**. Observed load versus mid-span deflection and the observed load versus strain for all ten tested beams are presented in this paper and discussed in the following sections.

Table 1. Summary of Beam Results

Beam Specimen	Helical Reinforcement Ratio	Concrete Compressive Strength, MPa	Load at Cover Spalling off, kN	Failure Load, kN	Yield Deflection Δ_y, mm	Ultimate Deflection Δ_u, mm	Displacement Ductility Index Δ_u / Δ_y
12HP25	0.113	100	372	411	40	240	6
8HP25	0.050	80	297	346	32	185	5.7
12HP50	0.057	100	386	340	35	193	4.6
8HP50	0.025	80	324	310	31	68	2.2
12HP75	0.038	100	388	310	32	65	2
8HP75	0.017	80	381	300	40	45	1.1
12HP100	0.028	100	398	260	33	52	1.6
8HP100	0.013	80	326	250	34	41	1.2
12HP160	0.018	100	413	150*	38	38	1
8HP160	0.008	80	376	94*	39	39	1

*the load dropped suddenly.

Table 2. Summary of Beam Measured Strains at 40 mm Depth

Beam specimen	Measured Top Surface Strain Just Before Spalling off Concrete Cover	Measured Strain at 40 mm Depth Just Before Spalling off Concrete	Measured Strain at 40 mm Depth Just After Spalling off Concrete	Measured Strain at 40 mm Depth at Failure Load
12HP25	0.00324	0.00154	0.00315	0.0146
8HP25	0.0034	0.001386	0.002716	0.012459
12HP50	0.00324	0.00144	0.00296	0.011
8HP50	*	0.001273	0.00163	0.009155
12HP75	0.00336	0.00139	0.00281	0.008
8HP75	0.0034	0.002077	0.0049	0.004867
12HP100	0.00336	0.00137	0.00263	0.0058
8HP100	0.003	0.00119	0.00157	*
12HP160	0.0034	0.0014	0.0014	0.0014
8HP160	0.0035	0.001824	0.001824	0.001824

*not available

5.1. Load Versus Mid- Span Deflection

The main differences between the two series of test beams are the helix bar diameter and the concrete compressive strength. In each series the helical pitch was varied so as to investigate the behaviour of over-reinforced HSC helically confined beams with different condition by using different helical confinement diameter and different concrete compressive strength. The difference between concrete compressive strength affects the ratio of (ρ/ρ_{max}). ρ_{max} is the maximum allowable tensile reinforcement ratio and has been defined by AS 3600 [11] as Equation 1 and ρ is the longitudinal reinforcement ratio as shown in Equation 2. For the beams confined with 12 mm diameter helix and 105 MPa concrete, the value of ρ/ρ_{max} is 1.55. For the beams confined with 8 mm diameter helix and 80 MPa concrete, the magnitude of ρ/ρ_{max} is 1.93.

$$\rho_{max} = \frac{0.34\gamma f_c}{f_{sy}} \quad (1)$$

$$\rho = \frac{A_s}{bd} \quad (2)$$

where

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

K_u = 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.

b = beam width

A_s = longitudinal reinforcement ratio

Figs. (**5a**-**5e**) and (**6a**-**6e**) shows the load-midspan deflection of the ten tested beams. These figures show the remark-

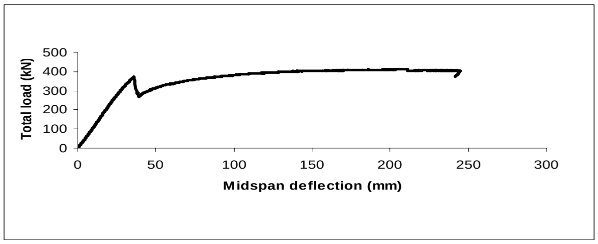

Fig. (5a). Load-deflection curve for beam 12HP25.

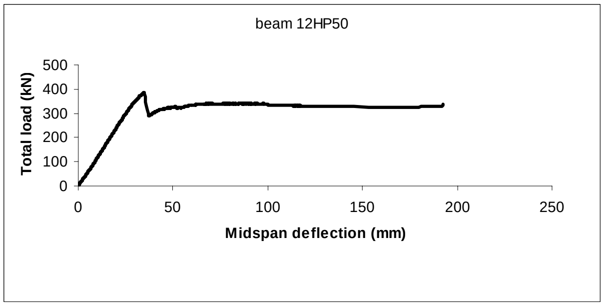

Fig. (5b). Load-deflection curve for beam 12HP50.

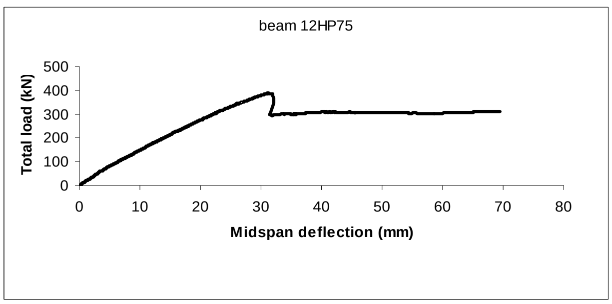

Fig. (5c). Load-deflection curve for beam 12HP75.

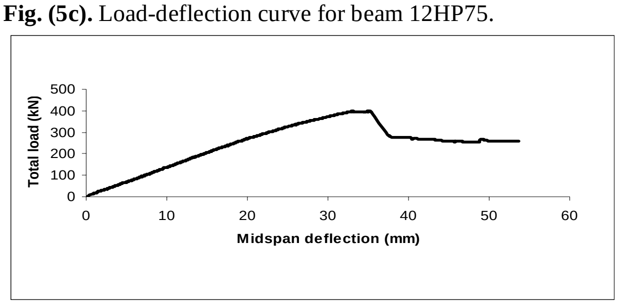

Fig. (5d). Load-deflection curve for beam 12HP100.

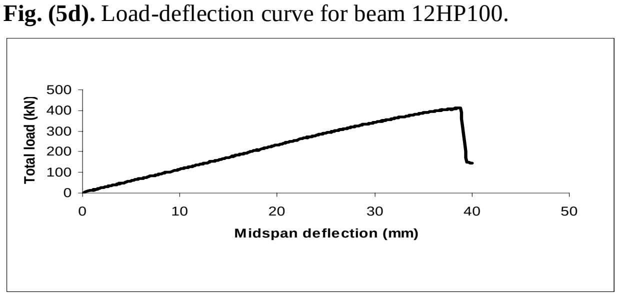

Fig. (5e). Load-deflection curve for beam 12HP160.

able effect of helical pitch on the 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 the helical pitch. 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.* [16] and Martinez *et al.* [17]. Fig. (**7**) shows the relation between the helical pitch and the ultimate mid-span deflection. Beams 12HP25 and 8HP25 had a maximum deflection of 240 mm and 185 mm, respectively and the deflection was reduced as the pitch was increased.

Deflection ductility index is defined as the ratio of ultimate deflection to the yield deflection. Fig. (**8**) shows that the deflection ductility index 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

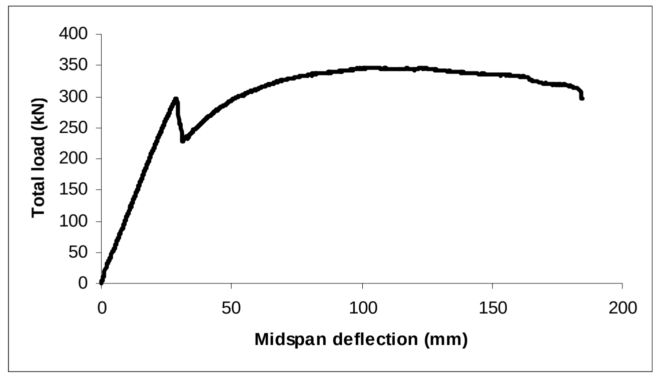

Fig. (6a). Load-deflection curve for beam 8HP25.

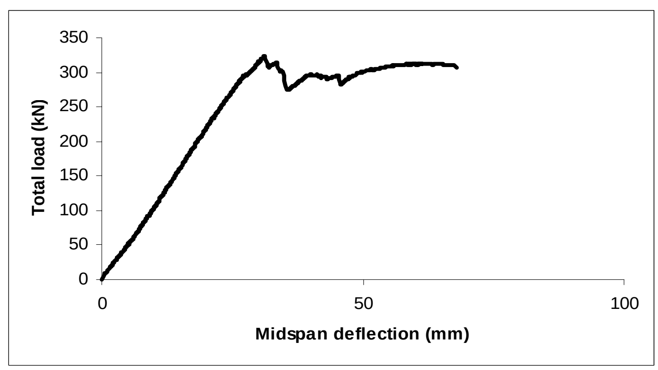

Fig. (6b). Load-deflection curve for beam 8HP50.

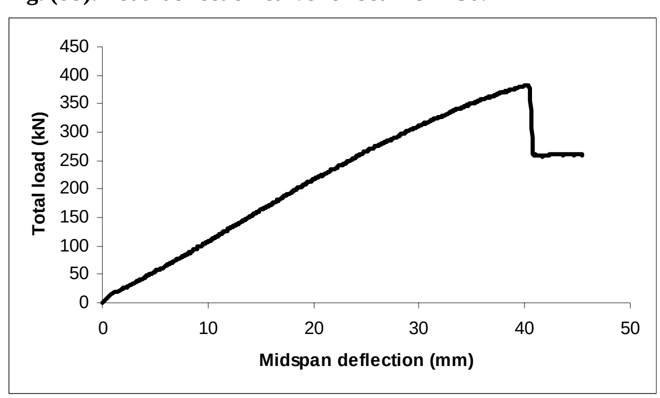

Fig. (6c). Load-deflection curve for beam 8HP75.

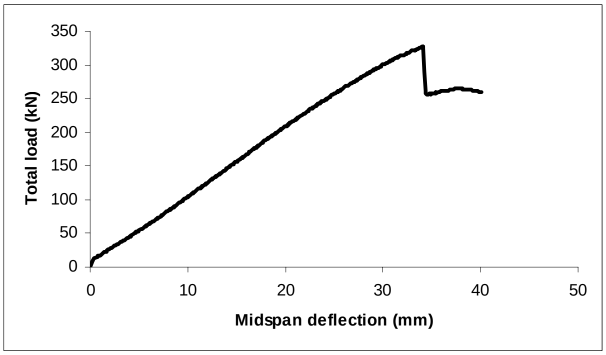

Fig. (6d). Load-deflection curve for beam 8HP100.

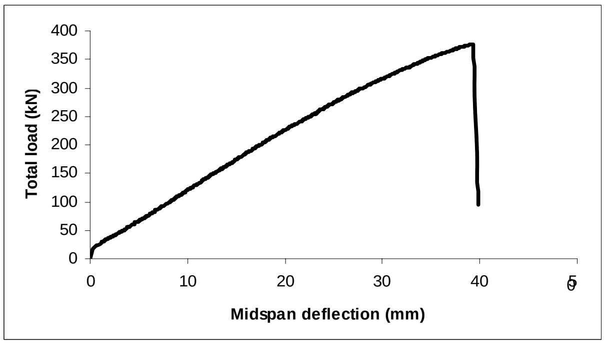

Fig. (6e). Load-deflection curve for beam 8HP160.

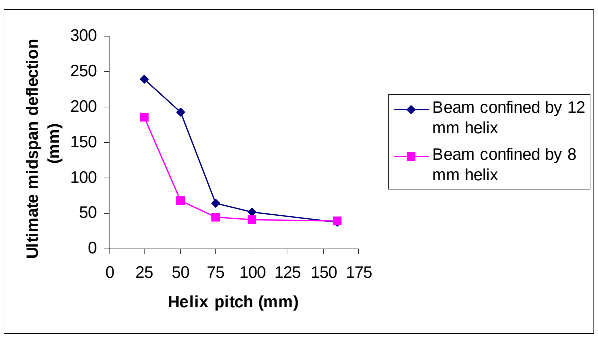

Fig. (7). Ultimate mid-span deflection versus helix pitch.

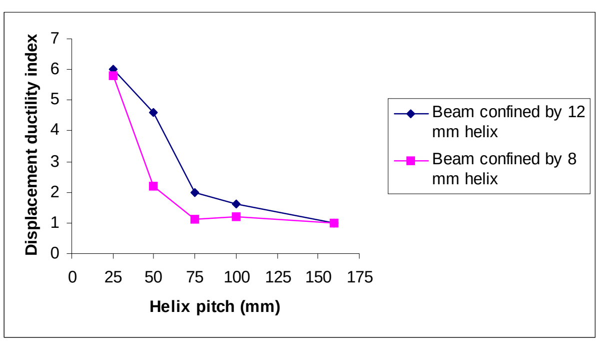

Fig. (8). Effect of helix pitch on normalized displacement ductility.

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. Helical pitch is an important parameter in enhancing the ductility of beams.

Fig. (**9**) shows the relation between the displacement ductility index versus the dimensionless quantity $\frac{\rho_h f_{yh}}{f_c'}$ where f_{yh} is the helical steel strength; f'_e is the concrete compressive strength and ρ_h is the volumetric helical reinforcement ratio expressed in Equation 3.

$$\rho_h = \frac{\pi d_h^2}{d_c s_h} \tag{3}$$

Where d_h = helix diameter

d_c = confined concrete core diameter

s_h = helical pitch

In this experimental program the confined concrete core diameter was 160 mm. A best fit linear regression curve was established and is shown in Fig. (**9**). From that curve it could be concluded that the brittle failure occurs when the $\frac{\rho_h f_{yh}}{f_c'} < 0.088$. For beams with $\frac{\rho_h f_{yh}}{f_c'} > 0.088$ 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 $\frac{\rho_h f_{yh}}{f_c'} > 0.314$. Then the ductile beam has $\frac{\rho_h f_{yh}}{f_c'}$ between 0.088 and 0.314. In other words, beam failure can change from brittle 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 the 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. Equation 1 shows that by increasing the concrete strength the maximum reinforcement ratio is also increased. As a result, the effective reinforcement ratio becomes below the maximum reinforcement ratio. Generally failure type changes from brittle to ductile by providing the

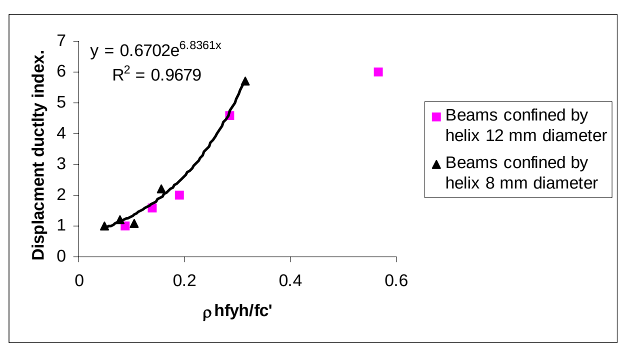

Fig. (9). Influence of helix reinforcement ratio on the displacement ductility index.

helix in the compression zone of over reinforced HSC beams.

5.2. Load Versus Strains

The strain at the top surface of the beam (concrete cover) was recorded to the point where the concrete cover spalled off.

Figs. (**10a**-**10e**) and (**11a**)-**11e**) show the measured load versus confined strain at 40 mm depth. Table **2** summarises

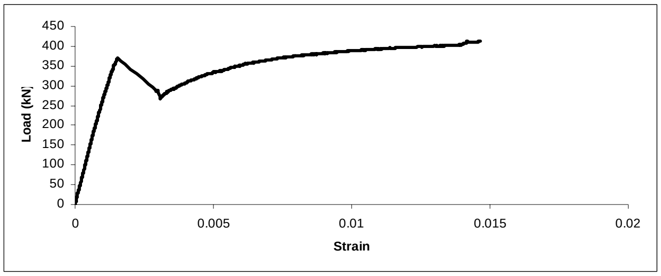

Fig. (10a). Load versus concrete compressive strain at depth 40 mm from top surface for beam 12HP25.

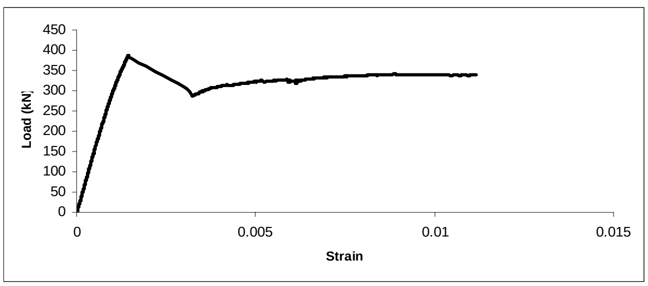

Fig. (10b). Load versus concrete compressive strain at depth 40 mm from top surface for beam 12HP50.

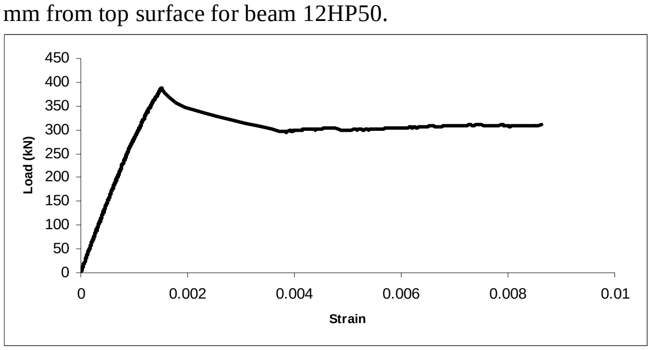

Fig. (10c). Load versus concrete compressive strain at depth 40 mm from top surface for beam 12HP75.

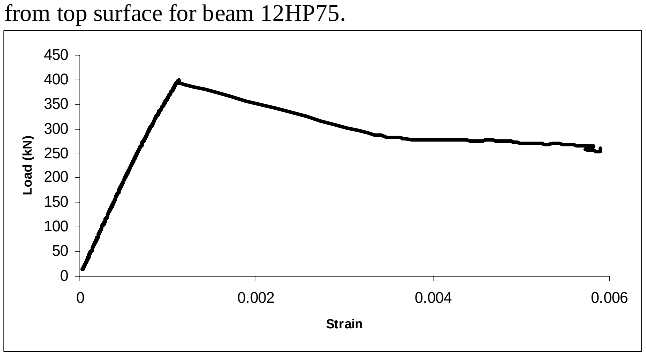

Fig. (10d). Load versus concrete compressive strain at depth 40 mm from top surface for beam 12HP100.

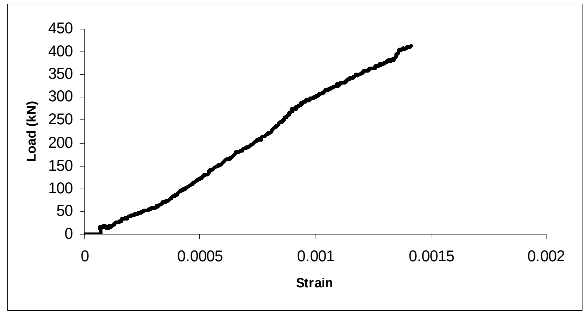

Fig. (10e). Load versus concrete compressive strain at depth 40 mm from top surface for beam 12HP160.

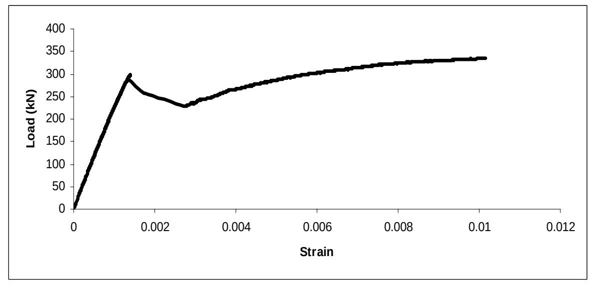

Fig. (11a). Load versus concrete compressive strain at depth 40 mm from top surface for beam 8HP25.

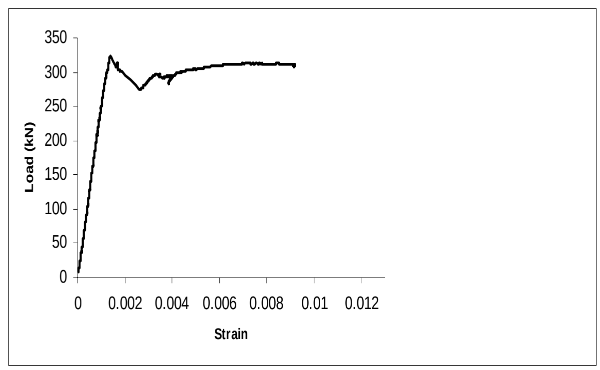

Fig. (11b). Load versus concrete compressive strain at depth 40 mm from top surface for beam 8HP50.

the measured confined strains at 40 mm depth and the concrete strains at the top surface of the beams just before concrete cover spalling off. The interesting point is that there was no significant difference between the concrete cover spalling off strain (top surface). However, the average concrete cover spalling off strain for the ten beams was 0.0033 which is in agreement with ACI 318R-02 [12] and AS3600 [11].

Fig. (**12**) shows the relation between the concrete cover spalling off load and helix pitch and Fig. (**13**) shows the relation between the failure load divided by the concrete spalling off load of the beams and the helix pitch. The beam 8HP75 is considered as experimental error. The Beam 8HP75 failed in a brittle mode, which was unexpected because for 75 mm helical pitch, the mode of failure should have been ductile. Also from the beams with 12 mm helical diameter, it is noted that the spalling off the concrete cover load for the beams, which have helical pitch of 50 mm and 75 mm was 386 kN and 388 kN, respectively, it is very similar, but the spalling

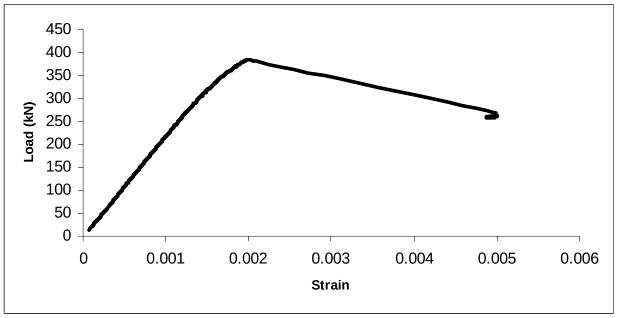

Fig. (11c). Load versus concrete compressive strain at depth 40 mm from top surface for beam 8HP75.

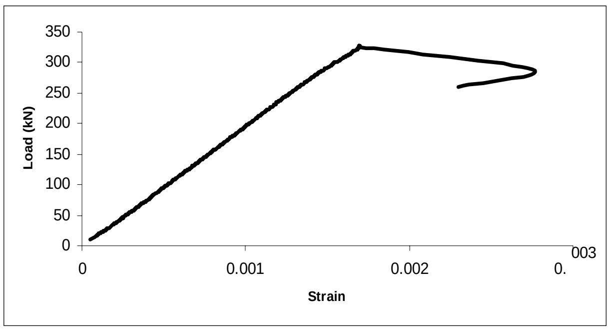

Fig. (11d). Load versus concrete compressive strain at depth 40 mm from top surface for beam 8HP100.

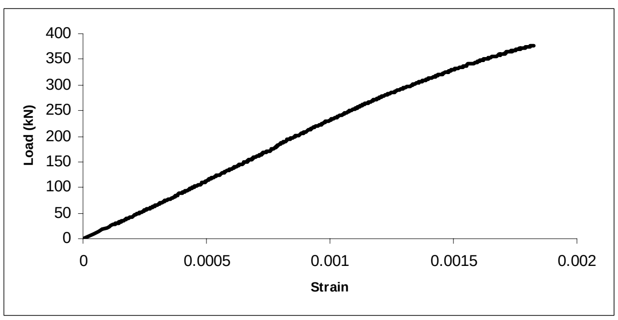

Fig. (11e). Load versus concrete compressive strain at depth 40 mm from top surface for beam 8HP160.

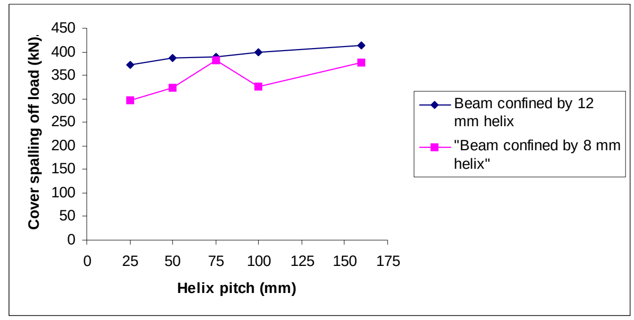

Fig. (12). Cover spalling off load versus helix pitch.

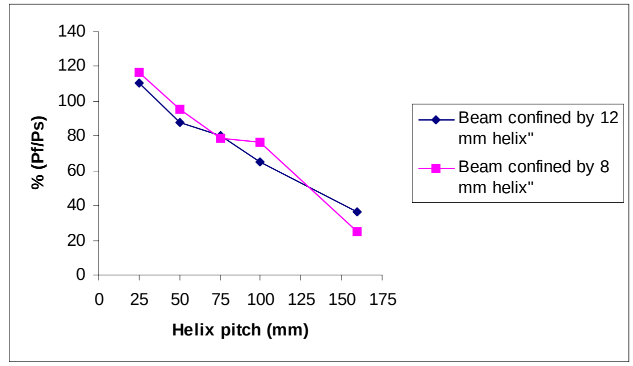

Fig. (13). (Failure load / cover spalling off load) as percentage versus helix pitch.

off concrete cover load of the Beam 8HP75 was 381 kN which is much more than the spalling off concrete cover load of the Beam 8HP50, which was 324 kN. Based on this, it can be considered that Beam 8 HP75 had an experimental error. It is worth noting that the spalling off load increased linearly as the helical spacing increased and the ultimate load decreased as the helical spacing increased. Based on these findings it can be concluded that the spalling off load is directly proportional to the helical pitch and the ultimate load is inversely proportional to the helical pitch.

It is a common belief that closely spaced reinforcement physically separates the concrete cover from the core, causing the early failure of the cover. That statement does not consider the effect of helical diameter or the other variables such as helical yield strength, concrete compressive strength and longitudinal reinforcement ratio, which may have significant effect. It is believed that cover spalling off occurs when the strain in between confined and unconfined concrete changes significantly. In other words, when the strain at the cover becomes less than the strain of the confined concrete, which does not follow the strain gradient as shown in Fig. (**14**). The experimental results presented in Figs. (**10a-e**) and (**11a-e**) and summarised in Table **2** prove that the sudden change in strain (energy release) causes spalling off the concrete cover. For example in beam 12HP25 the strain at 40 mm depth just before spalling off the concrete cover was 0.00154 and just after spalling off the concrete cover was 0.00315 (the strain at 20 mm depth is higher than the strains at 40 mm depth), this remarkable change in strain causes the spalling off the concrete cover. The beam 12HP160 has no sudden change in strain (strain energy release) because of the negligible effect of the confinement, where the maximum strain at the top surface of the beam was 0.0034 and the failure strain at 40 mm depth was 0.0014, which is lower than the strain at the top surface of the beam (no spalling off phenomenon).

The experimental results show considerable displacement ductility index for beams confined with helical pitch 25 and 50 mm. These results promote the use over reinforced beams in a structure safely by adding helical confinement in the compression zone of beams. In different structures such as, high-rise buildings and bridges, beams can be produced economically by increasing the longitudinal reinforcement ratio more than the maximum longitudinal reinforcement ratio allowed by the design codes and then the ductility can be improved effectively by confining the compression zone using helical confinement. In other words when the cross section of the beam is restricted and the beam strength required is more than the nominal strength of the beam if designed as an under reinforced section (the longitudinal rein-

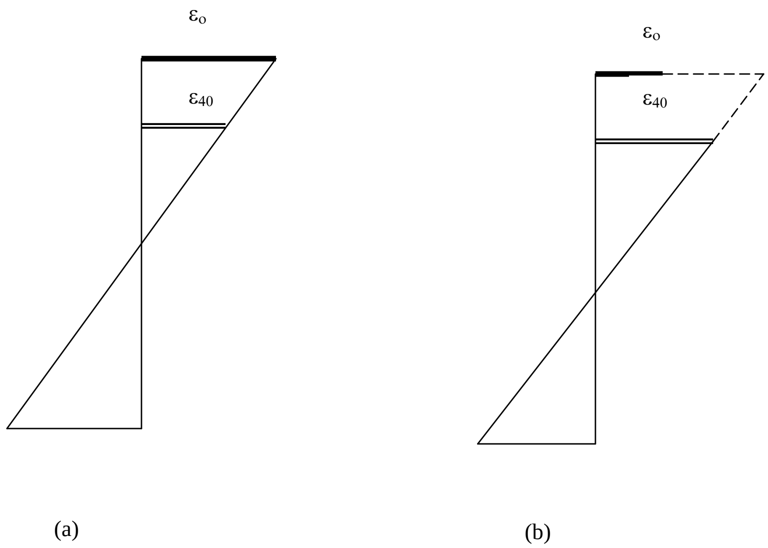

Fig. (14). (**a**) Strain distribution before loss of the concrete cover ($\varepsilon_o > \varepsilon_{40}$). (**b**) Strain distribution after spalling off the concrete cover.

forcement ratio is less than the maximum longitudinal reinforcement ratio allowed by the code), then it could enhance the strength up to the required strength by increasing the longitudinal reinforcement ratio and enhancing the ductility by confining the compression zone using the helical confinement with proper pitches.

6. CONCLUSIONS

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 mm and 12 mm.

The two beams with helical pitch of 160 mm (equal to the core diameter of the beam) have 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.

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 deflection 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. 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.

The common reason for the spalling off phenomena is that closely pitched helixes physically separate the concrete cover from the core. However, the experimental results show that the spalling off occurred when the strain in between confined and unconfined concrete changed significantly. This change is affected by the helical pitch as well as other parameters such as helical diameter and tensile strength. In other words, there is a considerable release of strain energy responsible for spalling off the concrete cover. The quantity of strain energy release is affected by different factors, one of which is helical pitch. Finally, this study has shown that adopting a suitable helix pitch can enhance the strength and confined compressive strain (ductility) of HSC beams reinforced with high strength steel.

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