COMPRESSIVE BEHAVIOUR OF CONCRETE CONFINED BY ARAMID FIBRE SPIRALS

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ABSTRACT

The paper reports the experimental results of compressive tests on concrete cylinders wrapped by aramid fibre spirals. Both circular concrete cylinders with a single spiral and rectangular concrete specimens with two interlocking spirals are investigated. Concentric compression tests were carried out. It was found that the behaviour of confined concrete is influenced not only by the concrete strength, but also the spiral leg spacing and the degree of interlocking. Concrete cylinders with close spacing and a high degree of interlocking usually gave higher strength and ductility. Experimental results are compared with analytical data.

KEYWORDS

Concrete, compression, aramid fibre, spiral, interlocking spirals, passive confinement.

INTRODUCTION

It is generally accepted that plain concrete exhibits a brittle failure when it is compressed, which leads to a rapid loss of load-carrying capacity. The concept of using spiral reinforcement is to restrain the concrete from expansion and thus delay the failure. In the past, a lot of research has focused on using steel spirals and rings to confine concrete (Ahmad and Shah 1982, El-Dash and Ahmad 1995, and Mander *et al* 1988). The increase in ductility and strength were prominent. With the advent of composite materials, replacement of steel by fibre-reinforced-plastic (FRP) seems to be a rational method to solve the corrosion problems. In addition, due to the difference in the stress-strain behaviour of FRP and steel, the induced confining pressure is also different when subjected to compression. The stress of steel remains virtually constant after its yield point so the induced pressure cannot increase after yielding. On the other hand, FRP possesses linear elastic properties. The stress of the FRP confinement keeps on increasing with strain, and thus a monotonically increasing confining pressure is produced. The maximum confining pressure is obtained when the ultimate strength of the confinement is reached. When further load is applied, failure of the confined concrete often occurs as a result of fracture of the confinement reinforcement. In order to verify this, an experimental programme was carried out and the results are described in this paper.

EXPERIMENTAL DETAILS

Single Spiral

Kevlar 49 aramid fibre was used to make the spirals. Ten yarns were used to form a bundle which was then formed into a spiral by impregnating with resin and wrapping round a mandrel (Leung 2000). The mechanical properties of the aramid bundle are listed in Table 1.

TABLE 1
MECHANICAL PROPERTIES OF ARAMID SPIRALS

Material	Cross-sectional area	Ultimate load	Ultimate stress	Ultimate strain	Elastic modulus
Kevlar 49 aramid (ten yarns)	1.75 mm^2 (including resin)	2.42 kN	1.38 GPa	1.53 %	90.1 GPa

In order to study the effect of spiral pitch on confined concrete, single spirals were fabricated with different spacings, (10 mm, 20 mm 35 mm and 50 mm), but the total height was fixed at 194 mm. Typical spirals are shown in Figure 1. Three polythene rods, which have a negligible contribution due to their low elastic modulus (4 GPa), were used to hold the spiral in space.

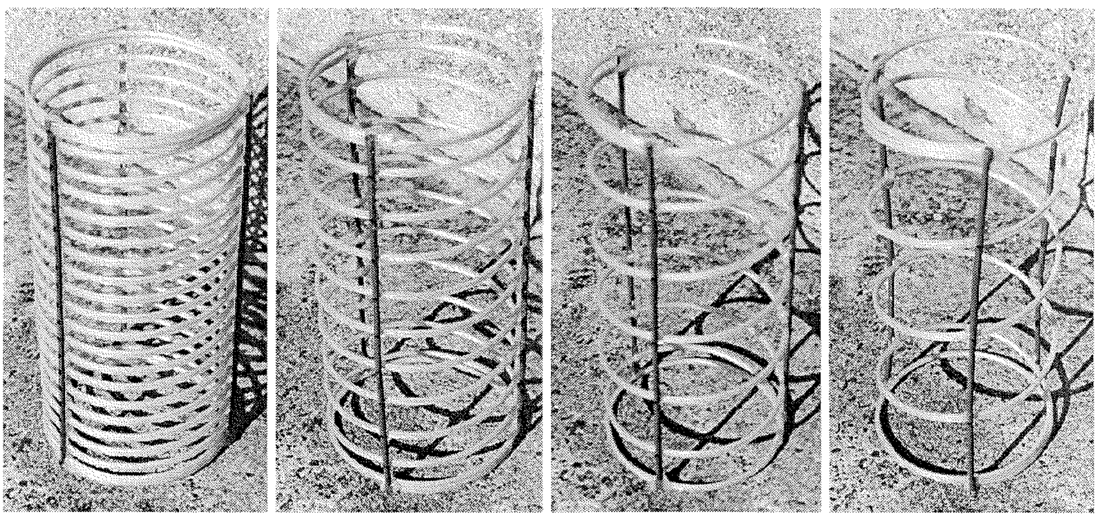

Figure 1: Aramid fibre single spirals

Double Interlocking Spirals

If the spirals are to be used to reinforce non-circular sections, some form of interlocking is required. To investigate this problem, two spirals with a fixed pitch of 20 mm, but with different centre-to-centre spacing were also tested. Typical interlocking spirals can be seen in Figure 2 which also shows the polythene rods used to maintain the necessary configuration.

With the diameter of the spiral (d_{sp}) fixed at 90 mm, five different centre-to-centre distances of adjacent spirals c_{sp} were utilized (36, 45, 57, 69 and 81 mm). These correspond to c_{sp}/d_{sp} ratios of 0.40, 0.50, 0.63, 0.77 and 0.90 respectively.

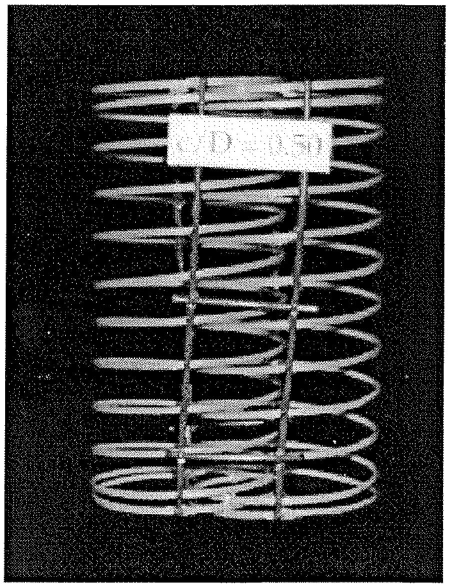

Figure 2: Double interlocking spirals

Concrete Specimens

The height of the concrete mould was 200 mm and the height of the spiral was 194 mm, so a thin 3 mm concrete cover could be provided at both ends. A 5 mm cover was provided around the outside giving an overall diameter of 100 mm. More details can be seen in Figure 3. It should be noted that the slenderness ratio adopted here is 2.0. This value was found to be the limiting value for the end effects to come into play (van Mier *et al* 1997).

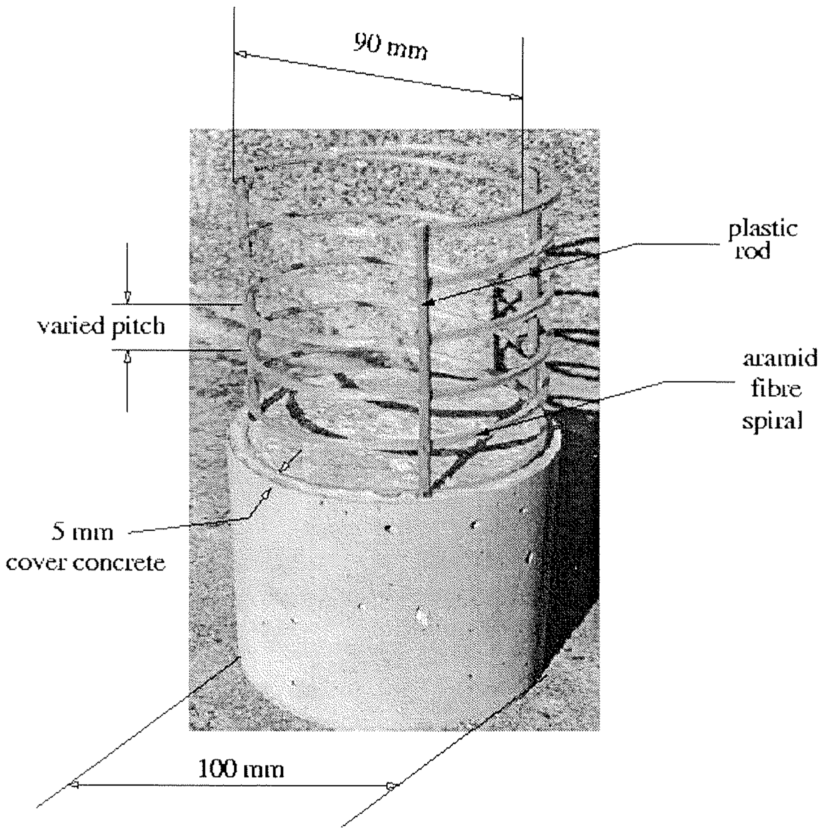

Figure 3: Details of specimen

Concrete cylinders with a single spiral and rectangular specimens with two interlocking spirals were cast. The concrete had a design strength of 40 MPa at 28-days. The concrete mix details are given in Table 2. The maximum coarse aggregate size was restricted to 5 mm, so that the aggregate particles could easily pass between the legs of the spiral. Ordinary Portland Cement was used with water/cement and aggregate/cement ratios of 0.45 and 4.5, respectively.

TABLE 2
CONCRETE MIX DESIGN

Material	Quantity, kg/m^3	Percentage by weight, %
aggregate (5 mm)	973	43.7
sand	703	31.6
OP cement	373	16.8
water	179	7.43

All the concrete specimens were cast in three lifts and each lift was followed by vibration on a shaking table. The specimens were then stripped from their moulds after one day and covered with plastic sheeting until the designated testing dates.

Forty two single spiral samples were tested and 12 with double interlocking spirals.

Loading Arrangements and Testing Procedures

All concrete specimens were tested in a 2000 kN concrete cube testing machine in a displacement controlled mode so that loading and displacement past the peak could be recorded. The loading rate adopted for all test was 0.3 mm/min. All specimens were preloaded with a load of 10 kN when the displacement reading in the data logger was adjusted to match that on the test machine. The test was continued until snapping of the spiral occurred.

For circular concrete specimens with a single spiral, tests were made at 8 days, 15 days and 28 days to obtain different compressive strengths. For the interlocking-spiral specimens, testing was carried out about 40 days after casting.

RESULTS AND DISCUSSIONS

Observations

For the concrete cylinders with a single spiral, it was observed that the longitudinal cracking of the cover concrete commenced near the mid-height of most samples. Such cracks gradually propagated to both ends with increasing load. When the load reached the concrete compressive strength, severe spalling of the cover occurred. However, it was noted that complete disintegration of the cover concrete did not occur. The cover failure was more noticeable in cylinders with closely-spaced spirals which physically separate the cover from the core. At the ultimate stage, fracture of the spiral, which occurred at mid-level of specimens, was sudden and explosive. Severe internal cracking was also noticed by examining the failed samples. It was observed that the core concrete has been reduced to fine rubble. Specimens after failure are shown in Figure 4.

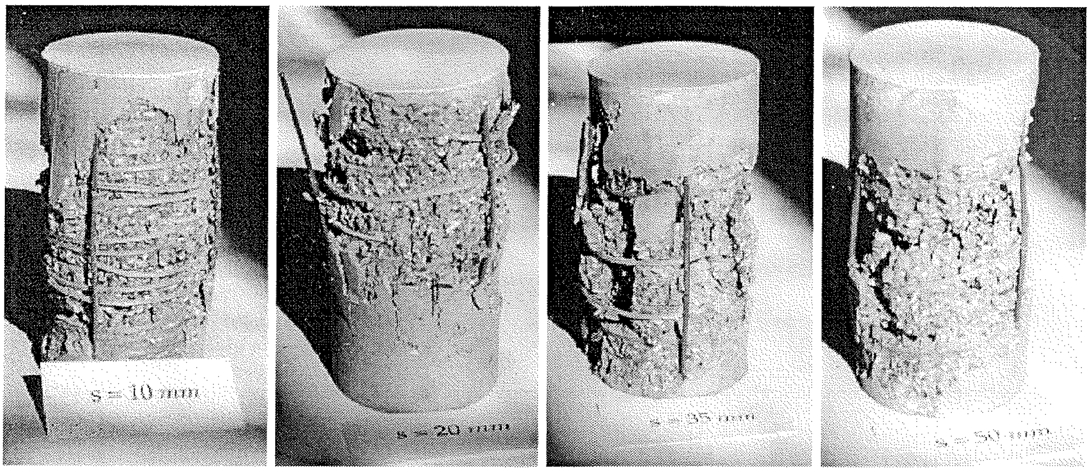

Figure 4: Concrete specimens at failure (single spiral)

For concrete specimens with double interlocking spirals, the breaking of the interlocked spirals was found to be less explosive due to the shielding effect of the cover concrete which varied in thickness. As with the case of a single spiral, no change in the spiral was visible prior to fracture, but extensive cracking could be observed. Typical concrete specimens at failure are shown in Figure 5.

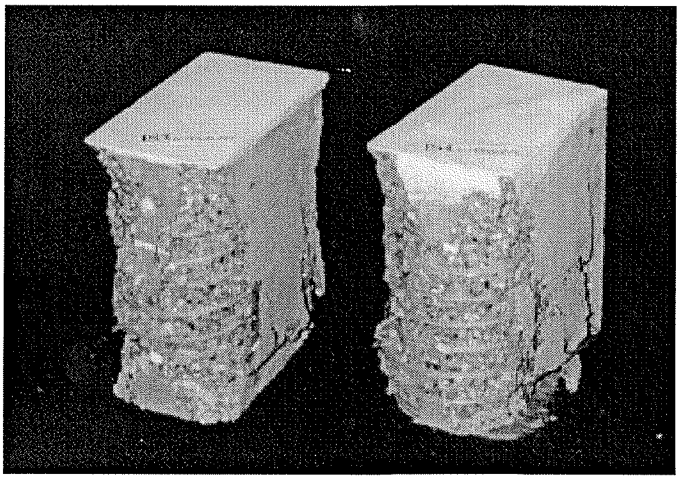

Figure 5: Concrete specimens at failure (double spirals)

Loading response

The experimental axial load-displacement profiles for single-spiral specimens are presented in Figure 6. All graphs are plotted to the same scale. The numerical results are also shown in Table 3. All data are averages of two or three specimens and the standard deviation (std.) of the data is also included. The theoretical prediction, which modifies the active confinement model (Kotsovos and Pavlovic 1995), is also given for comparison in the same table and figure (Leung 2000).

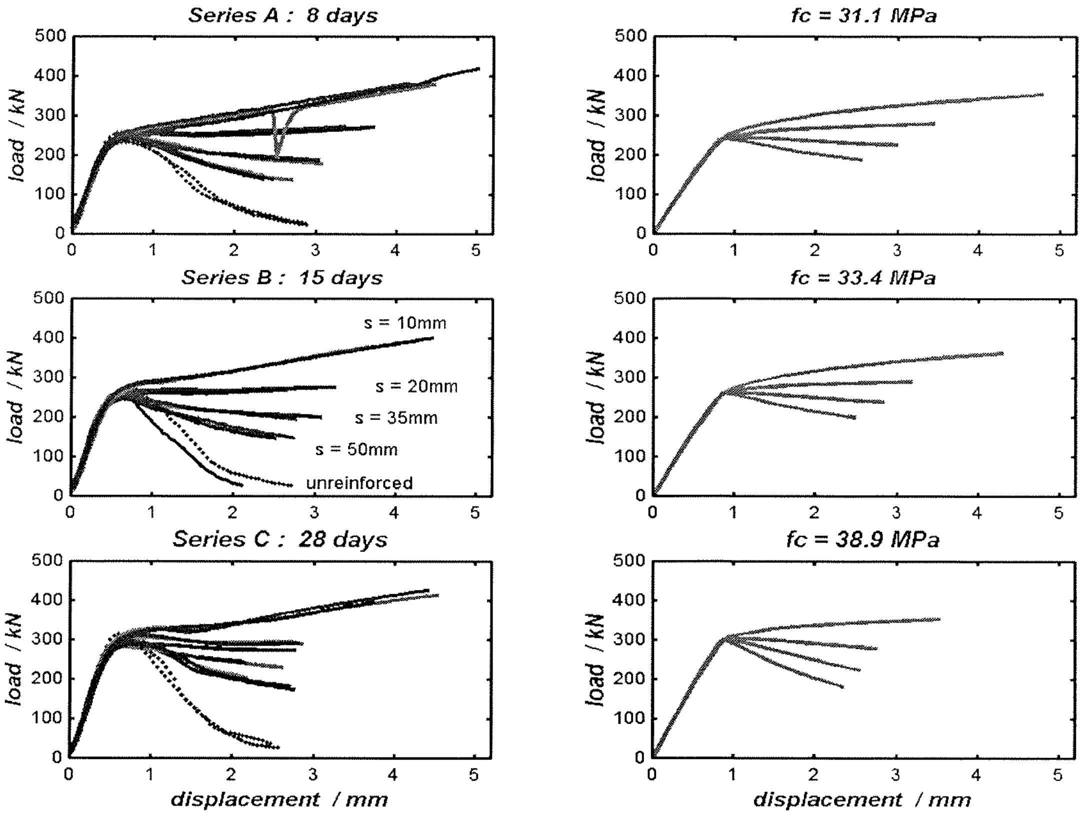

Figure 6: Experimental (on the left) and theoretical (on the right) results of concrete with a single spiral

TABLE 3

EXPERIMENTAL AND THEORETICAL DATA FOR CONCRETE CYLINDERS WITH SINGLE SPIRAL SUBJECTED TO UNIAXIAL COMPRESSION

Date of testing	Pitch mm	Maximum load kN	Displ. at max. load mm (std.)	Breaking load kN (std.)	Displ. when spiral breaks mm (std.)	Theoretical breaking displ. mm
	plain	243.9	0.622 (0.02)			
	50	245.3		137.9 (1.39)	2.510 (0.18)	2.562
8 days	35	242.4		184.4 (5.34)	2.990 (0.13)	3.007
[A series]	20	269.8		270.5 (2.07)	3.595 (0.20)	3.452
	10	392.9		392.9 (21.5)	4.555 (0.44)	4.790
	plain	262.3	0.629 (0.05)			
	50	252.1		149.9 (4.65)	2.560 (0.17)	2.497
15 days	35	249.9		197.8 (3.03)	2.877 (0.18)	2.851
[B series]	20	271.3		272.2 (3.70)	2.914 (0.30)	3.195
	10	389.2		391.0 (11.8)	4.170 (0.43)	4.303
	plain	305.8	0.643 (0.05)			
	50	294.4		186.1 (16.4)	2.570 (0.34)	2.348
28 days	35	287.9		237.7 (7.02)	2.637 (0.03)	2.555
[C series]	20	301.3		283.9 (9.00)	2.816 (0.04)	2.768
	10	412.8		412.2 (15.5)	4.240 (0.42)	3.543

Figure 6 shows that all specimens with a single spiral gave higher strength and strain values compared with unreinforced concrete cylinders, but the pre-peak behaviour is almost unaffected by the lateral reinforcement. Decreasing the spiral pitch increases the strain capacity of the specimens but only for the closest spacing is there a significant increase in failure stress. The lateral pressure created by the restraining effect of the spiral becomes larger at reduced pitch, so the confined concrete cylinder can sustain more loading before failure of the spiral occurs (see the last two columns of Table 4). However, this restraining effect does not become significant until the concrete cylinder approaches its ultimate axial compressive strength. The effect is delayed when higher concrete strengths are used; the specimen is stiffer, so the lateral expansion does not occur until later in the loading process. Thus, in series C with 10 mm pitch, there is a slight reduction in stress after the initial peak before the subsequent gain in strength caused by the spirals.

Supposing that the axial strain of plain concrete at peak load and the breaking strain of spirally confined concrete represent their ultimate values, the ultimate strain for confined concrete improves by about 4 times (for s = 50mm) and up to 7.5 times (for s = 10mm) compared with plain concrete (series A in Table 4). Figure 6 also shows that concrete strength strongly affects the magnitude of both the maximum strain and strength. When concrete with higher uniaxial strength is used, the strain magnification factor reduces slightly (see series C). Higher strength concrete cylinders display less ductility than the lower strength concrete cylinders. Lower strength concrete has a lower axial modulus and expands more transversely, which leads to longitudinal cracks and lower strength. But this behaviour allows more benefit to be achieved from the presence of spirals. In contrast, higher strength concrete usually gives lower ductility because high strength concrete itself is rather stiff and brittle. When high strength concrete cylinders are tested under uniaxial compression, comparatively little lateral expansion should be expected. A lower tensile force will then be generated in the spiral. When the high strength concrete cylinder reaches its ultimate state, disruption of the core concrete is found to be sudden and explosive due to the release of the large amount of energy inside the concrete matrix.

For the concrete specimens with interlocking spirals, the experimental data can be found in Table 4. The experimental results and the theoretical model are shown in Figure 7.

TABLE 4
EXPERIMENTAL AND THEORETICAL DATA FOR CONCRETE CYLINDERS WITH DOUBLE INTERLOCKING SPIRALS SUBJECTED TO UNIAXIAL COMPRESSION

c_{sp}/d_{sp}	Experimental breaking displacement (mm)	Theoretical breaking displacement (mm)
0.40	2.57	2.67
0.50	2.48	2.51
0.63	2.32	2.36
0.77	2.19	2.23
0.90	2.14	2.19

The specimen size increases with the centre-to-centre distance, so the increase in peak strength is purely due to change in specimen area, but the post-peak behaviour depends upon the spirals. It is found in Table 4 that, although the effect of c_{sp}/d_{sp} on the ultimate strain is rather small, it is worth noting that when the distance between the two spirals gets smaller, higher breaking strain values are recorded. So a high degree of overlapping leads to greater ductility. It should be understood that when two spirals are completely overlapped, the strain values would be enhanced as if the pitch is halved (see the curves for s = 10 mm and s = 20 mm in Figure 6). When c_{sp}/d_{sp} equals 1, there is no overlapping, so the ultimate strain would be identical to that of a single spiral.

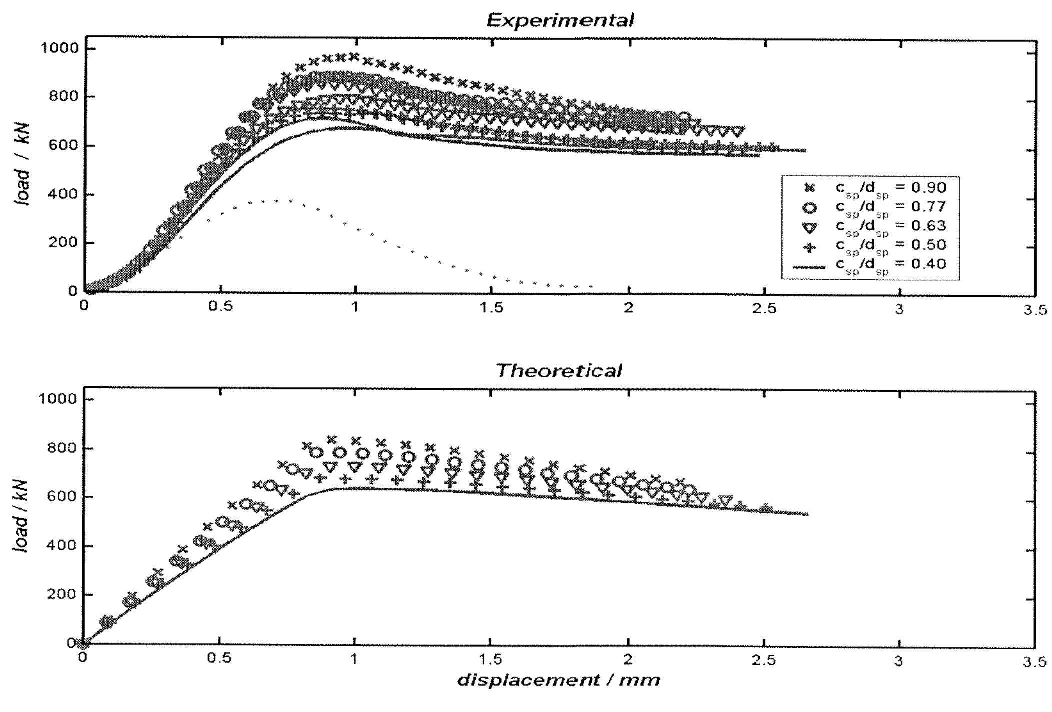

Figure 7: Experimental and theoretical results of concrete with double interlocking spirals

Good agreement between the experimental results and the theoretical prediction is found. Some general trends of the experimental data are also reflected in the theoretical results.

CONCLUSIONS

Concentric compression tests on short AFRP spirally-confined concrete cylinders have been described. The critical variables, including the concrete compressive strength, spiral spacing, arrangement of spirals and degree of interlocking, have been considered. A promising increase in strain is obtained experimentally and theoretically for a high degree of overlap. But a reverse situation is reported for high concrete strength and large spiral spacing. Bulging failure was found to be the governing mode for most uniaxially compressed concrete cylinders, which is usually followed by fracture of the spiral. On the analytical side, a fairly consistent prediction is made by the formulation reported elsewhere.

It is believed that by making use of such enhancements in the compression flange of beams, the strain and strength capacity of the beam should be increased.

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