CONCRETE CONFINED EXTERNALLY BY PRE-STRESSED STEEL STRAPS

By

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ABSTRACT

The target of this study is to investigate the behavior of concrete confined externally by pre-stressed steel straps when subjected to concentric load. Few parameters were studied with their effect on the response of confined concrete. The cross section shapes whether circular or rectangular and the developed confinement effect for each figure were considered. The configuration of the confining straps at the corners of prismatic concrete element was accounted in the research. Also, the spacing between the straps and its effect on the homogeneity of concrete confinement and the corresponding compressive strength was included, too. Last, the behavior of concrete when loaded at smaller width/area than its original geometric configuration was examined in the study. Thirty-four concrete specimens were tested to conduct the process of the research.

INTRODUCTION

Research work in the field of confined concrete is industrially important because of the consequent gain of strength and ductility. When concrete is subjected to extremely high or sudden loads, as in a case of earthquake or explosion, the limited ductility of the material detests. Behavior of confined concrete members has been studied extensively in the last two decades. The effect of lateral reinforcement is neglected up to 40-50% of the concrete maximum capacity, which is the actual working range. The real contribution of confinement takes place at higher range of loading when the lateral strains of concrete become high. The lateral dilation of concrete forces the lateral confining elements to stretch outside producing excessive internal strains and stresses. This behavior from the concrete towards the confining elements attracts passive pressure that enhances the strength of concrete. [Samaan et. al (1998), Chai et. al (1994), and Ahmad et. al (1991)]

Behavior of concrete under concentric compressive load is governed by bond stresses between the concrete paste and aggregates. When the applied load approaches the ultimate capacity of concrete, slippage between paste and aggregates occurs. This slippage is accompanied by crack initiation that propagates with the incremental increase of loading. If excessive lateral pressure is applied to the concrete, the contact bond will be stronger and the slippage between paste and aggregates will be delayed to a higher range of loading. When the confining reinforcement is sufficient to resume tolerable confining stress, the propagation of cracks will be slower than propagation of cracks for unconfined concrete. The slower rate of propagation causes the better ductility behavior obtained for confined concrete under compressive loading. [Sargin (1971)]

In the current research, it is targeted to investigate the response of concrete subjected to concentric compressive load, when it is confined externally by pre-stressed steel straps. The applied pre-stressing will generate active pressure on the concrete before applying the longitudinal compressive load. It will take the advantage of utilizing the enhanced behavior from the very early stage of loading instead of waiting to the passive pressure to be generated later as the case for confinement attracted by transverse reinforcement.

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The objective of the study is to initially predict the range of the enhancement would be gained by this method of confinement. This situation simulates the strengthening of an existing concrete column to sustain higher loads. In this stage, the study is limited to apply the confinement to raw specimens with no prior damage. The study may be extended in the future to rehabilitate damaged concrete.

EXPERIMENTAL PROGRAM

Methodology

The experimental program of this research was constructed to study the effect of external pre-stressed straps on the concrete behavior when subjected to concentric load. The enhancement gained by confinement depends on several physical and mechanical parameters that constitute the considered case. Circular cross sections used to gain more enhancement in strength due to lateral confinement than that gained by rectangular cross sections [Mander et. al (1998), Mau[(2)] et. al (1998), and Saatcioglu (1992)].

The sharp corners of the rectangular shape reduce the effective confinement magnitude and reduce the effectively confined area of the cross section as compared to that of circular section. For circular specimen, the confinement is almost uniform around the perimeter of the specimen. In case of prismatic specimen, the confinement is maximum at the corners and decreasing towards the middle of the sides. The effect of transverse reinforcement configuration on the magnitude of passive pressure and consequent enhancements has been investigated by Saatcioglu and Razvi (1998), Hajjar and Gourley (1996), and Chai et. al (1994). The current program included cylinder specimens as well as prismatic specimens to investigate the behavior of both shapes and to compare the results with respect to each other.

In addition, the external confinement distribution for rectangular cross section is more complicated because it is difficult to assure peer pressure at the sharp corners of the specimen. In the current study, round corner straps similar in shape to the stirrups of rectangular column was utilized. Another configuration was used as external confinement by utilizing right angled straps around the specimen to produce extended area of confinement all around the concrete perimeter.

Spacing between lateral confinement elements affects the homogeneity of the confinement along the height of concrete specimen. The closer the confining elements the better the response of the confined concrete. When the lateral pressure applied to the concrete is less than certain amount [Saatcioglu and Razvi (1998, and Chai et. al (1994)], the concrete experience no enhancement in strength or ductility due to confinement. Four different values of spacing between straps were scheduled and tested in the presented study.

Boundary loading conditions are very important in the behavior of concrete elements subjected to compressive load. The ratio between loading area and the dimensions of concrete specimen controls the stress flow through the element for a considerable height [Van Mier (1986)]. The response of concrete is the best when loading area equals the full cross sectional area of specimen. In such case, the stress is almost uniform along the height of the cylinder or prism, regardless the special effect at the ends due to boundary confinement. In the presented experimental study, the width of loading plate is varied to study the effect of loading area to height of specimen on the behavior of concrete. Four different plate sizes were scheduled and tested in the study for this purpose.

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Procedure

In order to operate the previously discussed methodology, thirty-four concrete specimens of 150x300-mm size were tested [Figure (1)]. Similar sizes have been tested by Mau[1] et. al (1998), Larralde (1997), Miramiran and Shahawy (1997), Alsayed (1992), and Ahmad et. al (1991)]. Four unconfined specimens were prepared as control cylinders to be a reference for the other results. The distribution of configuration and confinement for each specimen is shown in Table (1). The table classifies the shape of tested specimen whether cylindrical or prismatic in column (2). Column (3) presents the confining strap shape as if it is a hoop for cylinders, or rounded corner or right angled for prismatic specimens. Spacing between straps is varied as per figures given in the fourth column of the table. Meanwhile, width of loading plates at both ends of the specimen is shown in column (5) and measured in cms. The ultimate load could be sustained by concrete is shown for each test specimen in column (6). The seventh column presents the load enhancement ratio for each specimen as the outcome of dividing the maximum sustained load by the corresponding average load for the control specimens ***(P / P_c).*** The last column of the table includes the parameter, ***$(P / P_c)_{avg}$*** , which is the average of each two replicates those are identical in shape, confining strap spacing, and loading plate width.

High-strength steel bolts M12 have been utilized to generate the pre-tensioning in the straps. The strap was tightened using calibrated wrench to produce the required tension. The wrench was adjusted to sustain maximum torque that generates force of 18 kN in bolts. This choice was based on a near-yield stress required for the confining strap. The strap dimensions are 30 x 3 mm, which allow to have sustained stress of 20 kN/cm^2 under the above-mentioned tensile force. Specimens loaded at constant rate up to failure. Failed specimens are shown in Figure (2) for circular specimen number (8) and prismatic specimen number (20).

EXPERIMENTAL RESULTS

Effect of Strap Configuration

Due to the complexity of transverse confinement distribution in rectangular cross section concrete elements, it was targeted within the course of this study to investigate the effect of utilizing two alternative configurations of pre-stressed straps. The first is utilizing rectangular steel straps with round corners of 10-mm radius. This choice is easy in manufacturing and installation because of the tolerance allowed for adjustment between the strap and concrete. The other alternative is utilizing rectangular strap with right angles at the four corners. These right angles make the mission difficult in both manufacturing and installation because there is no tolerance allowed at all in both stages.

The outcomes of the experimental study show that the round corner technique is effective for narrow spacing. Figure (3) presents the enhancement comparison for both techniques utilized in the study. The enhancement ratio shown is the ratio between the strength of concrete specimen ***(f_{cc})*** to the corresponding strength of control specimen ***(f_{cco}).*** The compressive strength of concrete is enhanced by 58% when the spacing ***(s)*** between round corner straps is 40 mm center-to-center (***s / b*** = 0.27, where b is specimen side length) against 68% enhancement occurs when the right angle technique is utilized. For higher spacing the effectiveness of the second method become much better than the first one. When the spacing between straps reaches 8.5 cm (***s / b*** = 0.57), the strength enhancements is 10% and 40% for round corner and right angled straps, respectively. The loss of effective confinement of the first case and consequently the lower strength enhancement is referred to the variable distribution in effective confinement in horizontal as well as vertical directions.

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Effect of Cross Section Shape

It has been validated in earlier studies that confined cylindrical concrete specimen could gain higher strength enhancement than rectangular specimens when all physical and mechanical circumstances are alike. This was concluded based on passive pressure that develops in the transverse reinforcement in concrete subjected to compressive load. The results obtained in this study [Figure (4)] show similar behavior for concrete confined externally by pre-stressed straps. Cylindrical specimen gained enhancement in its strength varying from 44% to 84% when confined by straps with spacing varying from 8.5 cm to 4.0 cm. Corresponding enhancement in rectangular pattern was recorded within a range from 40% to 68% for the same spacing limits.

The above mentioned findings are similar to those obtained by Mander et. al (1998), Mau(2) et. al (1998), and Saatcioglu (1992) that the lateral confinement is not uniform for prismatic models. For cylindrical models, the confinement distribution is almost uniform along the perimeter of concrete. This difference in lateral confinement causes the effectiveness of confinement to be less for rectangular cross section. Hence, the strength enhancement for prismatic concrete specimens is less reacting than that for cylindrical specimens.

Effect of Loading Plate Width

The effect of loading conditions such as boundary status at top and bottom of the loaded concrete specimen is more sovereign for short specimens where the slenderness ratio, $\boldsymbol{b / H}$ (width to height), is less than five. Previous studies have shown that failure of concrete subjected to concentric load takes place at the mid-third of the specimen's height [Van Mier (1986)], for short specimens up slenderness ratio of 1/5. For slender specimens, the location of failure depends on the formation of the plastic hinge through the height of concrete specimen [Chai et. al (1994)]. This is referred to the effect of loading platens (top and bottom) on the adjacent zone of concrete within height equals approximately to the width or diameter of the cross section.

The other major parameter that affects the behavior of concrete with respect to loading condition is loading area. The larger the loading area and implicitly the width of loading plate, the better the load distribution through the concrete cross section. Additional stresses induced by narrowing the loading plate reduce the capacity of concrete unless the concrete is confined extensively for height enough to redistribute the stresses evenly through the cross section. This extensive confinement is used for cases like in end anchorage of pre-stressed girders or at the top of piers under bridge bearings.

The results in the current study recorded reduction in the strength capacity of concrete when the loading plate gets narrower. For circular cross section model, the strength enhancement decreases from 84% to just 1% when the loading plate width decreases from 15 cm ($\boldsymbol{t / d}$ = 1.0, where, $\boldsymbol{t}$, is the plate width and, d, is the specimen diameter) to 6 cm ($\boldsymbol{t / d}$ = 0.4) for the same confining condition. Figure (5) presents the results for concrete confined externally by 30x3 mm straps spaced at 40 mm apart center-to-center.

For rectangular cross section type, the enhancement of concrete strength dropped from 68% to (–7)% due to varying the loading plate width from 15 cm ($\boldsymbol{t / b}$ = 1.0) to 6 cm ($\boldsymbol{t / b}$ = 0.4). It worth at this point to stress that the enhancement in concrete strength due to external confinement could not compensate the reduction in strength due to utilizing narrower loading plate for the later case.

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ANALYTICAL STUDY

Several mathematical models have been proposed for confined concrete under concentric loads. Chi et. al (1994) and Hajjar and Gourley (1996) proposed analytical models representing the behavior of concrete fully jacketed by steel. Samaan et. al (1998) presented a mathematical model for the behavior of concrete confined by Fiber composites. A finite element model was introduced by Liu and Foster (1998) for confined concrete considering the actual steel stress in the transverse reinforcement.

The results obtained from the current study have been analyzed to deduce introductory indication for quantitative relationship between the different parameters included in the research and the response of confined concrete. However, since the number of tests conducted for each relationship is six to eight, it is not reliable to base a comprehensive formulation for the behavior of concrete confined by pre-stressed steel straps. Hence, the following quantification is indicative relationship, which still in need for more subsidiary tests and results.

Loading Plate Width

It was discussed previously in this paper that loading area affects the behavior of concrete when subjected to concentric load. In this session, a numerical relationship is presented to focus on the effect of loading plate width (or area) on the response of loaded concrete. Figure (6) and Figure (7) present the relationship between the ratio of (t/b) or (t/d) to the ratio of (f_{cc}/f_{cco}) where;

t = width of loading plates (cm),

b = side length of concrete specimen (cm),

d = diameter of concrete specimen (cm),

f_{cc} = ultimate compressive strength of confined concrete, and

f_{cco} = ultimate compressive strength of unconfined control specimen.

The proportional relationship between the two ratios is obvious from the figure. The following linear mathematical expressions were derived to best fit the recorded data.

$$f_{cc} = f_{cco} + 0.90\,(t/d) + 0.67 \quad \text{.......Eq. (1)}$$

for cylindrical specimens, and

$$f_{cc} = f_{cco} + 0.88\,(t/b) + 0.63 \quad \text{.......Eq. (2)}$$

for prismatic specimens.

Figures (6) and (7) show that the presented mathematical expressions have excellent predictive capability to anticipate the effect of load plate width on the strength of concrete specimens. The calculated R^2 value for both relationships are 0.98 and 0.93 for Equations (1) and (2), respectively. Moreover, it could be noticed from the figures, and comparing the recorded data with the best fitting line that the compressive capacity of concrete decreases in a higher rate when the width of loading plate becomes less than one half of the side length/diameter of the specimen. In addition, it should be considered that the above stated mathematical expressions are limited to the tested ranges of variables like concrete strength,

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pre-stressing force, lateral confining pressure, specimen size and dimension, size and configuration of strap, and strap material.

Spacing of Straps

The observed behavior of concrete confined by exterior pre-stressed steel straps and subjected to compressive force is similar in general to that of concrete confined by passive lateral pressure resulting from transverse reinforcement. Strap spacing affects the uniformity of the lateral confinement distribution along the height of concrete element. The closer the straps the more homogeneous the confining pressure on concrete. Figures (8), (9), and (10) are introduced to represent the relationship between (s/d) or (s/b) ratio and (f_{cc} / f_{cco}) ratio. The figures present the inverse relationship between the two ratios.

It is aimed within the scope of this study to present a numerical relationship that represents the effect of external lateral confinement on the compressive strength enhancement of concrete. The conclusion of this expression was based on regression analysis utilizing the observed data, as well as, the prime relationship that had been introduced by Richart (1928). The later included the relationship between the confinement pressure either from hydrostatic pressure or enclosing steel tube and the resulting ultimate compressive strength of concrete. This expression for confined cylindrical specimens is;

$$f_{cc} = f_{cco} + 4.0\, f_l \qquad \text{Eq. (3)}$$

where the confining pressure (f_l) is defined as

$$f_l = \frac{A_s \times f_s}{d \times s}$$ where;

A_s = area of confining steel

f_s = stress of confining steel

Equation (3) includes the spacing parameter implicitly in the term of the lateral confining pressure. The coefficient of (4.0) in this relationship is very close to that introduced by Richart, which was (4.1). It should be noted that Richart proposal was based on continuous confinement along the whole height of concrete samples, while the current proposal is based on discontinuous confinement. The above equation gives R^2 value of ***0.98*** when compared to the test results obtained from the conducted experimental tests for circular cross sections [Figure (8)].

A similar relationship is presented for the case of rectangular concrete cross section confined by straps [Figures (9) and (10)]. The relationship has the following form;

$$f_{cc} = f_{cco} + 2.8\, f_l \qquad \text{Eq. (4)}$$

for rectangular cross sections with right angled straps, and

$$f_{cc} = f_{cco} + 1.8\, f_l \qquad \text{Eq. (5)}$$

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for rectangular cross section with round corners, and

$$f_l = \frac{A_s \times f_s}{b \times s}$$

for rectangular cross section.

It can be noticed that the confinement coefficient dropped from (4.0) for circular cross section to (2.8) for rectangular concrete cross section confined by right-angled straps and to (1.8) when confined by straps with round corners. These changes reflect the effect of confinement distribution through concrete on the overall behavior and maximum compressive strength.

CONCLUSIONS

Thirty-four concrete specimens were tested to investigate the behavior of concrete confined externally by pre-stressed steel straps when subjected to concentric load. The specimens included four control samples to be a reference for other test results.

The following conclusions were derived from the study:

- Rectangular concrete cross section confined by straps with right angles has better performance than similar samples confined by straps with round corners specially when strap spacing gets larger.

- It is recommended to utilize straps at spacing about one half of the diameter or side length of concrete cross section. However, the concrete cross section and width of strap are the governing parameter for the final choice to weigh the gained enhancement and the corresponding economy of the application.

- Circular cross sections of concrete elements enable more benefit of lateral confinement than rectangular cross section can do. The strength enhancement encountered by concrete with circular cross sections is about 40% higher than enhancement encountered by concrete with rectangular cross section. The confinement distribution along the sides of rectangular cross section is more condensed at the corners and the middle of the section than it at the mid-sides. This unequal distribution reduces the gained benefit from the lateral confinement.

- Loading area or loading plate width affects the ultimate strength of concrete subjected to concentric load. The tests showed that the direct proportional relationship between the compressive strength and loading plate width is getting steeper when the plate width is less than one half of the cross section diameter or side length. For wider plates the strength is improving linearly having the best response when the cross section is fully loaded.

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Table (1) Matrix of experimental Program and results

1	2	3	4	5	6	7	8
#	**Cross Section**	**Strap Shape**	**Strap Spacing (s) (cm)**	**Load Plate Width (t) (cm)**	**Load (kN)**	**P/Pc**	**(P/Pc)avg**
1	Cylinder	Hoop	8.5	15	640	1.42	1.44
2	Cylinder	Hoop	8.5	15	660	1.47	
3	Cylinder	Hoop	7	15	695	1.54	1.57
4	Cylinder	Hoop	7	15	720	1.60	
5	Cylinder	Hoop	4	15	840	1.87	1.84
6	Cylinder	Hoop	4	15	820	1.82	
7	Cylinder	Hoop	7	6	455	1.01	1.01
8	Cylinder	Hoop	7	6	450	1.00	
9	Cylinder	Hoop	7	8	550	1.22	1.19
10	Cylinder	Hoop	7	8	520	1.16	
11	Cylinder	Hoop	7	12	625	1.39	1.38
12	Cylinder	Hoop	7	12	620	1.38	
13	Cylinder	N/A	N/A	15	440	0.98	1.00
14	Cylinder	N/A	N/A	15	460	1.02	
15	Prism	Round Corners	8.5	15	525	1.05	1.10
16	Prism	Round Corners	8.5	15	570	1.14	
17	Prism	Round Corners	7	15	660	1.32	1.30
18	Prism	Round Corners	7	15	640	1.28	
19	Prism	Round Corners	4	15	770	1.54	1.58
20	Prism	Round Corners	4	15	805	1.61	
21	Prism	Right Angled	8.5	15	680	1.36	1.40
22	Prism	Right Angled	8.5	15	720	1.44	
23	Prism	Right Angled	7	15	720	1.44	1.49
24	Prism	Right Angled	7	15	765	1.53	
25	Prism	Right Angled	4	15	810	1.62	1.68
26	Prism	Right Angled	4	15	870	1.74	
27	Prism	Right Angled	7	6	450	0.90	0.93
28	Prism	Right Angled	7	6	475	0.95	
29	Prism	Right Angled	7	8	570	1.14	1.17
30	Prism	Right Angled	7	8	600	1.20	
31	Prism	Right Angled	7	12	680	1.36	1.35
32	Prism	Right Angled	7	12	670	1.34	
33	Prism	N/A	N/A	15	475	0.95	1.00
34	Prism	N/A	N/A	15	525	1.05	

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