Parameters Affecting the Behavior of Reinforced Concrete Wrapped With CFRP Sheet

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Abstract

In this paper the behaviors of strength and deformation of short reinforced concrete column specimens wrapped with CFRP were studied through testing 48 cylindrical specimens under axial loading. The role of parameters of CFRP wrap layers and arrangement, concrete strength , main steel reinforcement , lateral reinforcement and specimen slenderness ratio was studied. Results indicated that due to wrapping with CFRP layers the state of confined concrete occurs and the properties of strength and deformation are modified considerably. The ultimate load percentage was found to vary from 123% to 280% of that of unconfined specimens. The ductility of reinforced concrete specimens was found to be increased considerably as a result of wrapping. The effect of wrapping was found to be important in the case of concrete of lower strength and poorly reinforced with both main bars and lateral reinforcements. In order to obtain higher load capacity of wrapped high strength concrete it should be reinforced highly with both types of reinforcements. In general the parameters influencing the behavior reinforced concrete confined with CFRP sheets are: number of layers, replacing layers with strips, concrete compressive strength, main bars, lateral reinforcement, and specimens slenderness ratio. An analytical model was proposed for calculating ultimate load capacity and load-strain relationship for reinforced NSC and HSC confined with CFRP sheets. The predictions were found to be accurate, and the ratio of test / calculated ultimate load was found to be 1.0043 for NSC and 1.0033 for HSC.

Keywords: Axial strain, Column, Confined concrete, High strength concrete, Lateral strain, Strengthening, Wrapping

العوامل المؤثرة على تصرف الخرسانة المسلحة المغلفة بصفائح الكاربون

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الخلاصة

في البحث الحالي تم دراسة خواص المقاومة والتشوهات لنماذج من العمود الخرسانى المسلح القصير والمغلفة بصفائح الكاربون من خلال فحص 48 نموذجا تحت الحمل المركزي. تم دراسة تأثير عوامل عدد و ترتيب طبقات صفائح الكاربون, مقاومة الخرسانة, حديد التسليح الاساسي والجانبي, نسبة النحافة للنماذج. اكدت النتائج ان بسبب التغليف تم حصول حالة الحصر و تعديل خصائص المقاومة والتشوهات. أظهرت النتائج أن نسبة الحمل الاقصى تتغير من 123% الى 280%. أن مطيلية الخرسانة المسلحة قد ازدادت بشكل ملحوظ بسبب الحصر بالصفائح. أن تأثير الحصر كان مهما في النماذج قليلة المقاومة ذات تسليح اساسي وجانبي قليل. للحصول على اكبر مقاومة للحمل للخرسانة عالية المقاومة المحصورة يجب تسليحها بشكل جيد بالحديد الاساسي والجانبي. بشكل عام ترتيب العوامل المؤثرة على تصرف الخرسانة المسلحة المحصورة بصفائح الكاربون هي: عدد الطبقات, تبديل الطبقة بالشريحة, مقاومة الخرسانة, حديد التسليح الاساسي, حديد التسليح الجانبي, نسبة النحافة للنماذج. تم تقديم طريقة للتنبؤ بالحمل الاقصى و علاقة الحمل- الانفعال للخرسانة المسلحة المحصورة بالياف الكاربون. وجد بان نسبة الحمل المختبرى/النظرى يساوى 1.0043 للخرسانة عادية المقاومة و يساوى 1.0033للخرسانة عالية المقاومة.

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1- Introduction

Strengthening of reinforced concrete received considerable emphasis throughout the world and the issue of upgrading existing civil engineering infrastructures took a great deal of importance compared with new constructions. Many techniques and procedures for strengthening of the structural member are adopted where the level of strengthening depends on strength and deformation demands of the members. The strengthening in particular is important to increase the live-load capacity e.g. of a building that changes its use from residential to commercial [13]. Problems related to using steel plate for strengthening led to an alternative solution which is the use of Fiber Reinforced Polymer composites commonly known as FRP's. Fiber-wrapping technology was first used in practice for concrete chimneys in Japan; this concept then was extended to retrofit concrete columns [3]. Strengthening using fibers has been widely used for both bridges and buildings and for concrete surfaces in tension and compression. This scheme has also a beneficial effect in seismic region by enhancing ductility and increasing shear strength to the extent that brittle shear failure is converted to a ductile one [15].

Lin and Chen [10] found that the strength of confined normal strength concrete cylinders increased in direct proportions by the increase in composites layer number. *Ilki et al* [8] showed that for very low strength concrete there is a significant increase in compressive strength. Test results obtained by *Lam and Teng* [9] indicate that insufficient confined cylinders behave like the unconfined ones with similar failure pattern and a slight or almost no increase in the peak compressive stress. *Harries and Kharel* [6] and *Esfahani and Kianoush* [4] found that there is an increase in compressive strength and ductility of the wrapped cylinders due to confinement effect imposing a more ductile stress-strain behavior as compared to unconfined one. Tests by *Park et al* [12] indicated that wrapping concrete with strips instead of full wrapping lead to CFRP fracture mode of failure and the applied load was higher when the spacing between CFRP strips reduces and exhibits larger ductility. They also found that the differences in cylinders height have no significance on effectiveness of CFRP reinforcement. Test results by *Berthete et al* [2] indicated a significant increase in strength and ductility but the confinement efficiency decreased when the compressive strength of the specimens increased. Also they found that when the confinement level is high, there will be more enhancements in structural ductility. *Tamuzs et al* [16] noticed that the existing of steel bars help in increasing the rigidity and stress level of concrete cylinders where the steel bars lead to a uniform increase in stress. They also found the presence or absence of reinforcing bar does not change the second portion characteristic of the deformation diagram of wrapped specimens.

Most of the studies were conducted on plain concrete having compressive strength ranges from 20 to 30 MPa and there are few number of researches clarifying the effect of reinforcement on the behavior of confined concrete. Because of the widespread use of high strength concrete in building structures, it is important to study the mutual combined influence and interaction when using high strength concrete with steel reinforcement and CFRP sheets wrapping on the behavior of confined concrete. The experimental work presented in this paper included testing cylindrical concrete specimens reinforced with steel bars provided both axially and laterally and wrapped with CFRP laminate. A comparative study was carried out to illustrate the role of important parameters affecting the strength and deformation of reinforced concrete wrapped with CFRP sheets.

2-Experimental Program

2-1 Materials:

Ordinary Portland cement [Type I] was used in the tests for producing both NSC and HSC mixes. Natural river sand was used as fine aggregate of (2.71) specific gravity at saturated surface dry condition and fineness modulus equal to 2.78. Natural river gravel and crushed gravel of maximum aggregate size equal to 12 mm were used. Results of sieve analysis indicated that the grading conforms to ASTM C33-03 [1] specifications limits. The specific gravity for the aggregates used were 2.74 and 2.68 with dry bulk density of 1860 kg / m^3 and 1740 kg / m^3 for natural gravel and crushed gravel, respectively. High range water reducer of Sika®Viscocrete®-20 Gold (liquid) [(type G) according to ASTM C494/C 494M-05a] of constant dosage equal to 2.5% by cement weight was used for preparing HSC mixes. CFRP of SikaWrap®-230C type was used for the purpose of wrapping specimens which is a unidirectional woven carbon fiber fabric having the following properties: elastic modulus is 238 GPa, tensile strength is 4300 MPa, and ultimate tensile strain is 1.8%. For bonding CFRP sheets to the concrete adhesive epoxy of Sikadur®-330 type was used which consisted of two component impregnation resin on epoxy resin base, mixed together in a ratio equal to (1: 4). All concrete specimens were reinforced with longitudinal compression reinforcement consisting of two types of hot-rolled deformed bars of ϕ10 mm and ϕ16 mm diameter. Deformed bars of ϕ6 mm diameter were used as transverse reinforcement in a shape of ties and spiral. Concrete cover equal to 15 mm was provided. Table (1) shows the properties of the steel bars used.

Table (1) Properties of the Steel Reinforcement Used in the Present Study

Bar Type	Yield Stress (MPa)	Ultimate Tensile Stress (MPa)	Elongation (%)
ϕ16 mm	531.4	682.3	18.74
ϕ10 mm	427.8	668.7	13.73
ϕ6 mm	594.5	629.5	8.2

2.2 Mix Proportion:

Thirteen trial mixes were prepared to get the optimum mix proportion for HSC of cube compressive strength equal to 80 MPa and the mix was found to be 1:1.2:1.8 (cement :sand : gravel , by weight). For NSC mix design was carried out to obtain a concrete of compressive strength equal to 45 MPa and the mix proportion was found to be 1:1.6:2.

2.3 Molds:

According to the dimensions of the specimens two types of mould were used in the present study. The first one was the standard cylindrical metal mold of 152 × 304.8 mm dimensions. For specimens of larger length a height was equal to 750 mm in which three standard cylinders were connected together by the mean of welding. Spacers were used to omit the extra space and to obtain a height equal to 750 mm.

2.4 Casting and Curing:

The steel reinforcement cage was put in the center of the cylindrical mould after omitting a bottom concrete cover equal to about 15 mm by putting a small amount of mix, then the mixture was poured in four layers each layer was compacted 25 strikes using 18mm diameter standard steel road as recommended for compacting plain concrete in ASTM C470/c 470M-03a specification. [1] Later a further compaction was made by striking the molds gently with a rubber hammer to exclude the remained air bubbles. The top surface of the concrete then finished by the mean of trowel and the specimens were left inside the mold for 24 hours to harden. After remolding the specimens were put in a water tank inside the laboratory to cure with a temperature kept to be (25± 3 Cº). At the end of curing, the specimens were removed from the water tank and left in the laboratory to dry for 14 days before wrapping with carbon fiber reinforced polymer (CFRP) sheets.

2.5 Wrapping Procedure:

After drying, the surface of all specimens intended to be wrapped by CFRP sheets was well cleaned by a steel brush to remove any dirt and dust. After brushing process which was done accurately and homogenously, the surface of specimens was cleaned again and prepared to be covered with the epoxy material, then CFRP layer was cut and prepared according to the surface area to be wrapped. The preparation of CFRP sheets is followed by painting cylinders faces with epoxy carefully using soft paint brush. It was made sure that the epoxy was equally and homogenously distributed at a constant thickness over the whole surface of the specimens. The process of providing epoxy was followed by pasting CFRP sheets on each specimen carefully and according to the variables requirements of each specimen. A steel roller was used in order to distribute the epoxy on the CFRP layer to allow for good impregnation and to ensure that all entrapped air bubbles disappeared. After wrapping the specimens were left to cure within 7 days according to manufacturer's recommendation.

2.6 Capping procedures:

Before testing, all the specimens were capped according to the recommendation of ASTM C617-03 specification.[1] The capping process is important to ensure a plane surface in order to distribute the load uniformly. For capping, gypsum paste was prepared; the dry gypsum was sieved on No.16 sieve to remove the deleterious substances. The steel base for capping device was filled with gypsum paste and the specimen was put on its inverted position and left for 30 minutes. After gypsum hardening the specimens were taken from the steel base and the extra portions of gypsum at the sides of the cylinders were removed.

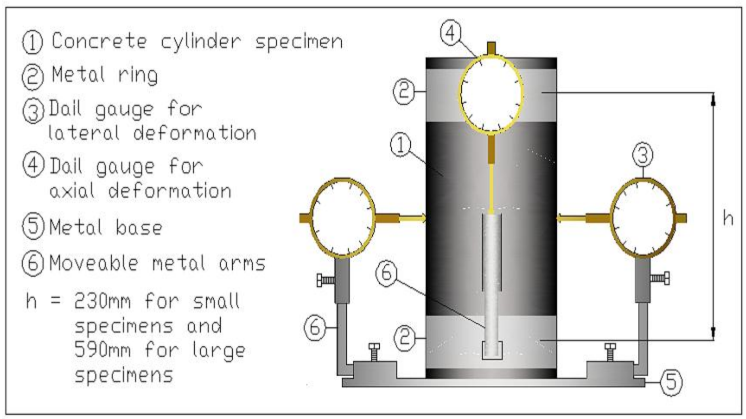
2.7 Test Measurements and Instrumentation:

The cylinders were tested and loaded to failure under increasing compressive load using the computerized testing machine of type (Walter + Bai AG/ Switzerland / 08 – 2003). The maximum capacity of the machine is 3000 kN. The rate of loading was constant and kept to be 0.3 MPa/sec for control specimens and 0.5 MPa/sec for wrapped ones. The load applied continuously without shock or impact till failure of the specimen. All measurements of axial and lateral deformations were recorded using a digital video recorder, to obtain accurate data especially near failure in which the deformation value is high and using the classical method via stopping the machine and taking the results leads to significant errors. Figure (1) shows the arrangement of the specimen at testing indicates the measurement units. For each concrete mix batch two cubes of 150 mm dimension were tested, and the cube compressive strength was taken as the average of the two values. Later, cylinder compressive strength was calculated by multiplying the value of cube compressive by 0.8 for normal strength concrete as proposed by Neville and Brooks [11] and by 0.88 as suggested by Yi et al [19] for HSC.

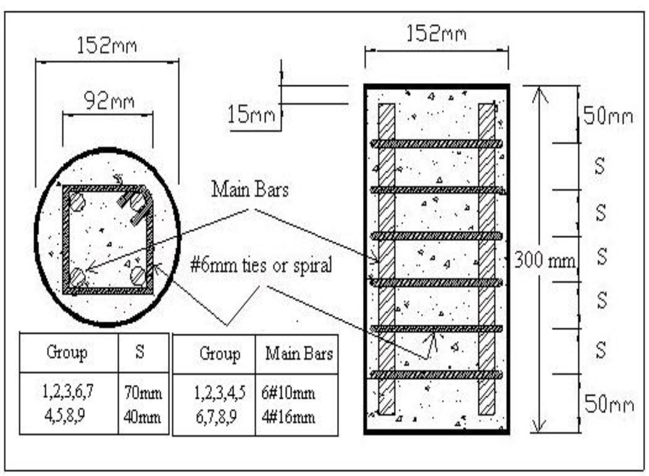
2.8 Details of Test Specimens:

According to the tested variables a total of 48 cylindrical specimens were prepared. The variable attempted to be studied in the present work are : (a) number of CFRP layer, (b) effect of replacing sheets with strips of CFRP, (c) amount of main reinforcement, (d) amount of lateral reinforcement, (e) concrete compressive strength, (f) type of lateral reinforcements, and (g) specimen height. Figures (3) and (4) show the dimensions and reinforcement details of the two types of specimens. The detail of specimens can be seen in the tables.

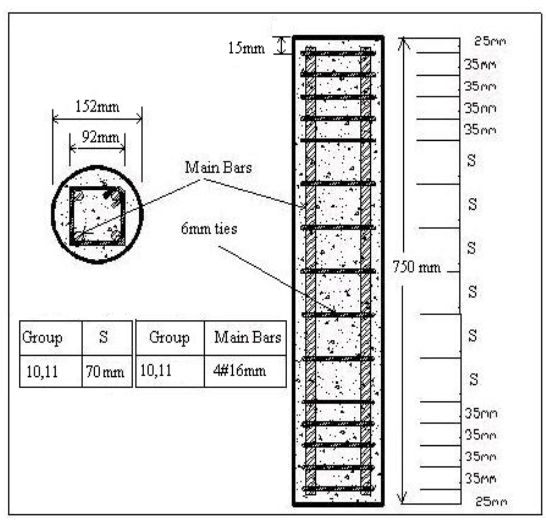
Figure(1) View of Specimen during testing



Figure(2) Schematic View of Specimen and Measurement Units



Figure(3) Reinforcement Details of Short Specimen



Figure(4) Reinforcement Details of Long Specimen

The first item of the specimen's code is the type of concrete, N for normal strength and H for high strength concrete, the second item is the specimen height; it is either 300 mm or 750 mm. The third item is the longitudinal or main reinforcement which is 10 mm diameter or 16 mm diameter, the forth item is the type and the spacing between the lateral reinforcement, T is used for ties and S for spiral, 70 and 40 are spacing between ties in mm. The last item is the arrangement of CFRP layers, C for control specimens without confinement while W is for wrapped specimens, the number beside W represent number of layers and P is for specimens wrapped with strips provided at the outer layer of CFRP sheet. The distance between strips and their width were constant and equal to 35 and 50 mm, respectively. According to the number of main bars provided to the specimens, the longitudinal compression reinforcement ratios were equal to 2.59% and 4.04%. It should be pointed out that to prevent failure of the end of specimens near the test machine platens and to ensure failure in the central zone of the specimens extra strips of 50mm were provided at ends of all specimens.

2.9 Concrete Strain Measurements:

The lateral strain in specimens was measured by using two dial gauges with accuracy equal to 0.01 mm displacement, placed at 180^o apart, attached and located to the mid-height of each specimen. They were placed on an especially fabricated metal base with adjustable and moveable metal arms to control the required position as illustrated in Figure (2). To measure axial displacement, one dial gauge was placed with accuracy equal to 0.01 mms displacement, attached to the cylinder by especially manufactured metal ring and located at the top third part of the cylinder. The axial strain was obtained by dividing the displacement by the gauge length (230 mm for small specimens and 590 mm for large specimens) and the lateral strain was obtained by dividing the average reading of the two dial gauges by the specimen's diameter.

3- Results and Discussion

3-1 Ultimate Load Capacity of Wrapped Concrete:

As a result of wrapping, a state of confined concrete usually occurs and accordingly the behavior of concrete becomes different in strength and deformation compared with plain concrete. Tables (2) (3) and (4) contain the results of ultimate load capacity of wrapped and unwrapped control specimens. The Tables also contain the percentages of ultimate load for wrapped to that of control specimens. Compressive strength of confined concrete (f'_{cc}) also calculated and shown in the tables. The compressive strength of confined concrete was obtained by calculating the load resisted by the concrete divided by the net concrete area. The load resisted by the confined concrete (Pc) is the total load (P_u) minus the load resisted by the axial steel reinforcement (P_s). The later load value is obtained by multiplying the yield stress of steel by the steel area. Figure (5) shows the variation of ultimate load percentage with the number of layers of CFRP for Group (1), (2), (4) and (5) specimens. For normal strength concrete specimens the percentages are 179%, 245% and 280% for specimens wrapped with one, two and three layers, respectively. While for high strength concrete the percentages of ultimate load are smaller and equal to 123%, 146%, and 168% for one, two and three layers of CFRP, respectively. Therefore, the effect of wrapping reinforced concrete with CFRP is more important for the case of NSC compared with HSC. It is observed from Figure (5) that the response of ultimate load with the number of layers for HSC is linear, while that of NSC slightly deviates from linearity especially when the number of layers is more than two layers.

Table (2) Results of Load and Strains for Group (1),(2) and (3) Specimens

Group	Specimen Code	Compressive strength (MPa)		$P_{u,\ test}$ (kN)	Composite Compressive Strength f'_{cc} (MPa)	Percentage of $P_{u,\ wrapped}$ / $P_{u\ plain}$	Maximum Axial Strain $\varepsilon_{au,\ Max}$	Maximum Lateral Strain $\varepsilon_{ru,\ Max}$	Dilation Ratio
		fcu	f'c						
Group (1)	N-300-10-T70-C	57.94	46.35	783.4	32.918	-	0.0039	0.0121	3.103
	N-300-10-T70-W1	54.44	43.55	1400.7	67.84	179%	0.0084	0.0156	1.857
	N-300-10-T70-W2	58.57	46.85	1921.5	97.309	245%	0.0197	0.0161	0.817
	N-300- 10-T70-W3	51.5	41.20	2197.1	112.902	280%	0.0172	0.0064	0.372
	N-300-10-T70-W1P	53.36	42.68	1605.1	79.4079	205%	0.0073	0.0158	2.16
	N-300-10-T70-W2P	49.73	39.78	2018.9	102.82	258%	0.0152	0.0186	1.223
Group (2)	H-300-10-T70-C	79.6	70.05	1475.4	72.06	-	0.0048	0.0123	2.563
	H-300-10-T70-W1	75.8	66.70	1807.5	90.895	123%	0.0029	0.015	5.172
	H-300-10 -T70-W2	82.8	72.86	2147.1	110.073	146%	0.0033	0.0063	1.909
	H-300-10-T70-W3	79.3	69.78	2482	129.021	168%	0.0122	0.0074	0.607
	H-300-10-T70-W1P	81.2	71.46	2138.7	109.598	145%	0.0048	0.0098	2.042
	H-300-10-T70-W2P	77.5	68.20	2483	129.08	168%	0.0078	0.0079	1.013
Group (3)	H-300-10-S70-C	79.79	70.22	1142.9	53.26	-	0.0033	0.0034	1.03
	H-300-10-S70-W1	78.38	68.97	1785.9	89.637	156%	0.0071	0.0013	0.183
	H-300-10-S70-W2	74.08	65.19	2231.8	114.866	195%	0.0157	0.0066	0.42
	H-300-10-S70-W3	70.82	62.32	2552.2	133.022	223%	0.0163	0.009	0.552
	H-300-10-S70-W1P	71.78	63.17	1932.5	97.932	169%	0.0214	0.0054	0.252
	H-300-10-S70-W2P	75.78	66.69	2331.7	120.52	204%	0.0186	0.0081	0.436

Table (3) contains results of the ultimate load capacity for Group (4) and (5) specimens. Such specimens were reinforced laterally with Ø 6 mm ties at 40 mm spacing, instead of 70 mm spacing. The percentages of the ultimate load for wrapped NSC specimens are 199%, 274% for one and two layers, respectively and equal to 137% and 181% for one and two layers, respectively for HSC specimens. For NSC the ratio is higher by 62% using one layer of CFRP and higher by 93% using two layers. Such ratios for Group (1) and (2) specimens are 56 % and 99%.

Table (3) Results of Load and Strains for Group (4),(5),(6) and (7) Specimens

Group	Specimen Code	Compressive strength (MPa)		$P_{u,\ test}$ (kN)	Composite Compressive Strength f'_{cc} (MPa)	Percentage of $\frac{P_{u,\ wrapped}}{P_{u\ plain}}$	Maximum Axial Strain $\varepsilon_{au,\ Max}$	Maximum Lateral Strain $\varepsilon_{ru,\ Max}$	Dilation Ratio
		fcu	f'c						
Group(5) Group(4)	N-300-10 -T40-C	64.52	51.62	765.2	31.88	-	0.0083	0.0135	1.627
	N-300- 10 -T40-W1	60.87	48.69	1519.6	74.571	199%	0.0063	0.0086	1.365
	N-300- 10 -T40-W2	64.46	51.57	2096.8	107.228	274%	0.0157	0.0046	0.293
	H-300- 10 –T40-C	77.76	68.43	1469.3	71.725	-	0.0109	0.0097	0.889
	H-300-10 -T40-W1	80.09	70.48	2010.3	102.334	137%	0.0099	0.0024	0.243
	H-300-10 -T40-W2	81.49	71.71	2652.3	138.657	181%	0.0167	0.0068	0.407
Group (6)	N-300-16 -T70-C	42.15	33.72	812.1	22.185	-	0.0043	0.0103	2.395
	N-300-16 –T70-W1	62.61	50.09	1484.1	60.936	183%	0.0149	0.0075	0.504
	N-300-16 –T70-W2	50.44	40.35	1736.6	75.496	214%	0.021	0.0166	0.791
	N-300-16-T70-W3	59.5	47.60	2169.2	100.42	267%	0.0265	0.0159	0.6
	N-300-16-T70-W1P	42.67	34.14	1481.1	60.762	182%	0.0231	0.0134	0.58
	N-300-16-T70-W2P	42.15	33.72	2085.2	95.598	257%	0.0126	0.0134	1.063
Group (7)	H-300- 16 –T70-C	76.1	66.97	1362.3	53.91	-	0.0023	0.0047	2.043
	H-300-16 –T70-W1	73	64.24	2061.2	94.214	151%	0.0041	0.0039	0.951
	H-300-16 -T70-W2	75.58	66.51	2566.7	123.364	188%	0.0073	0.0064	0.877
	H-300-16-T70-W3	79.29	69.78	2891.7	142.105	212%	0.0125	0.0078	0.624
	H-300-16-T70-W1P	77.74	68.41	2151.3	99.409	158%	0.0079	0.0043	0.544
	H-300-16-T70-W2P	76.22	67.07	2675.9	129.66	197%	0.0135	0.007	0.519

Therefore, the difference between the percentage of ultimate load capacity of wrapped NSC and HSC is only marginal due to the change of spacing between lateral reinforcement. It is obvious from the results of Figure (5) that the percentage of ultimate load usually increases when the spacing between ties reduces especially for larger number of CRFP layer. Therefore to obtain higher load capacity especially for larger number of CFRP wrapped concrete attention must be offered to the arrangement of lateral ties because such type of reinforcement besides the wrapping with CFRP have a significant effect of buckling and collapse of concrete where the change of spacing between the ties from 70 mm to 40 mm will increase the load capacity of wrapped concrete by a ratio of 14% to 35 % regardless the effect of concrete strength. Results of ultimate load of Group (3) specimens are shown in Table (2) and in Figure (6). The percentages of ultimate load are 156%, 195% and 223% for one, two and three layers of CFRP layers, respectively. Accordingly, there is an increase in the percentage of ultimate load varied from 23% to 55% as a result of using spiral instead of ties in the concrete wrapped with CFRP.

In general, both types of lateral reinforcement and spacing between them are considered important factors in concrete after it confined with CFRP layers regardless of the number of layers provided, and the compressive strength of unconfined concrete. The best arrangement is the spiral type of lateral reinforcement with smaller spacing between rounds as far as possible. Table (4) and (5) contain test results and ultimate load capacity for wrapped specimens reinforced with four Ø 16 mm bars. In Group (6) and (7) specimens of the ratio of main bars which is equal to 0.0443 are nearly two times higher than that provided by Group (1) and (2) specimens. The percentage of the ultimate load for the wrapped HSC specimens are 151%, 188%

Table (4) Results of Load and Strains for Group (8),(9),(10) and (11) Specimens

Group	Specimen Code	Compressive strength (MPa)		$P_{u,\,test}$ (kN)	Composite Compressive Strength f'_{cc} (MPa)	Percentage of $P_{u,\,wrapped}$ / $P_{u\,plain}$	Maximum Axial Strain $\varepsilon_{au,\,Max}$	Maximum Lateral Strain $\varepsilon_{ru,\,Max}$	Dilation Ratio
		f_{cu}	f'_c						
Group (8)	N- 300-16 - T40-C	56.75	45.40	735.8	17.494	-	0.0026	0.014	4
	N-300-16-T40-W1	41.71	33.37	1326.8	51.892	180%	0.0111	0.0065	0.586
	N-300-16-T40-W2	54.38	43.50	1565.4	65.658	213%	0.0284	0.0121	0.426
Group (9)	H-300- 16 -T40-C	92.96	81.80	1096.6	38.591	-	0.0068	0.0019	0.279
	H-300-16 -T40-W1	86.89	76.46	1794	78.81	164%	0.0295	0.0093	0.315
	H-300-16 -T40-W2	86.05	75.72	2396	113.52	218%	0.0248	0.0069	0.278
Group (10)	N-750-16-T70-C	55.33	44.26	794	21.14	-	0.0099	0.0415	4.192
	N-750-16-T70-W1	45.07	36.056	1315.9	51.237	166%	0.0051	0.0051	1
	N-750-16-T70-W2	53	42.40	1899.5	84.889	239%	0.0136	0.033	2.427
Group (11)	H- 750-16 -T70-C	86.89	76.46	1356.9	53.601	-	0.0034	0.0412	12.118
	H-750-16 -T70-W1	75.31	66.27	1957.2	88.217	144%	0.0034	0.0182	5.353
	H-750-16 -T70-W2	79.14	69.64	2267.8	106.128	167%	0.0101	0.031	3.069

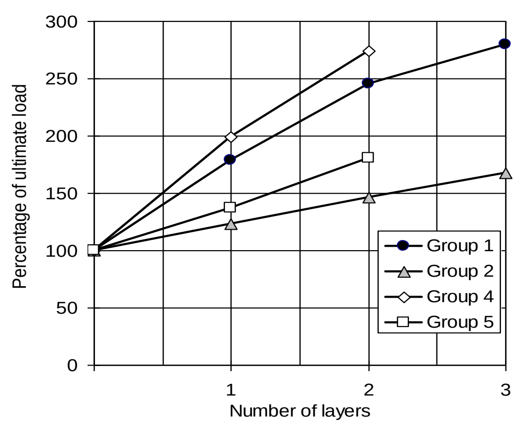


Figure (5) Percentage of Ultimate Load with Number of CFRP Layers[Group (1), (2),(4) and(5)Specimens]

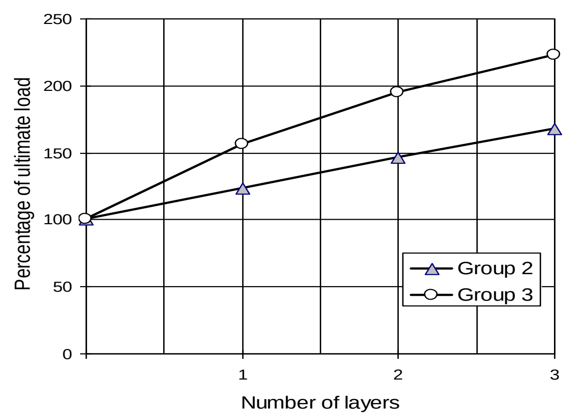
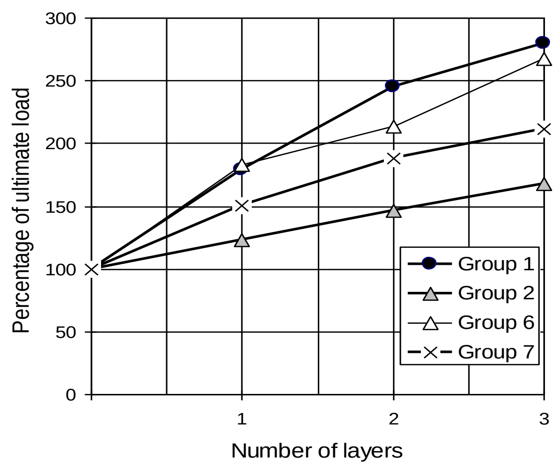


Figure (6) Percentage of Ultimate Load with Number of CFRP Layers [Group (2) and (3) Specimens]

and 212% for one, two and three layers of CFRP, respectively. For NSC, such ratio is 183%, 214 % and 267% for one, two and three layers, respectively. The difference between these values are 32%, 26 % and 55%, which are smaller than that of Group (1) and (2) specimens which are 56%, 99% and 112% for one, two and three layers respectively. Therefore, the difference in the ultimate load capacity of wrapped concrete with CFRP between HSC and NSC reduces when the amount of main bars increases. Accordingly, using HSC confined with CFRP sheets is more suitable for the case of concrete section which contains high amount of main bars.

From Figure (7), one can observe that changing the amount of main bars from 6 Ø 10 mm to 4 Ø16 mm has a slight effect on the percentages of load capacity of the wrapped NSC specimens where the percentages varied from 1% to 31% difference between Group (1) and (6) compared to percentages of 13 % to 44% between Group (2) and (7) where there is a positive effect in the change in the amount of main bar on the load capacity of the wrapped HSC. Therefore the performance of HSC to be wrapped with CFRP sheets is better when the amount of main bars is high. Table (4) contains the results of ultimate load and percentages of the ultimate load for Group (8) and (9) specimens. Figure (8) shows the variation of the ultimate load percentages with the number of layers. The percentages of the ultimate load are 180% and 213% for one and two layers of CFRP for those specimens made from NSC. For HSC specimens, the percentages are 164% and 218%. Therefore the difference between these values for the two types of concrete is not important because the difference between the two groups varied from 5% to 16%.



Figure(7) Percentage of Ultimate Load with CFRP Layers Number [Group (1), (2), (6) and (7) Specimens]

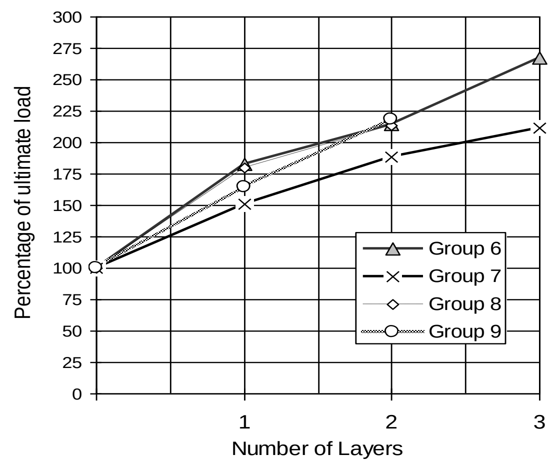


Figure (8) Percentage of Ultimate Load with CFRP Layers [Group (6), (7), (8) and (9) Specimens]

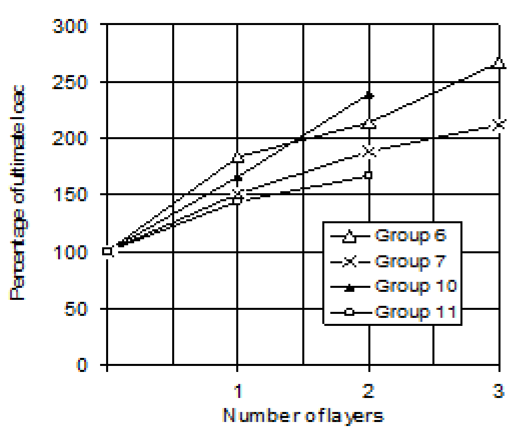
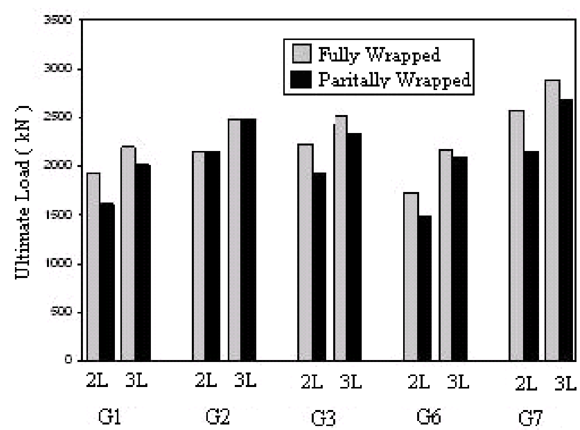
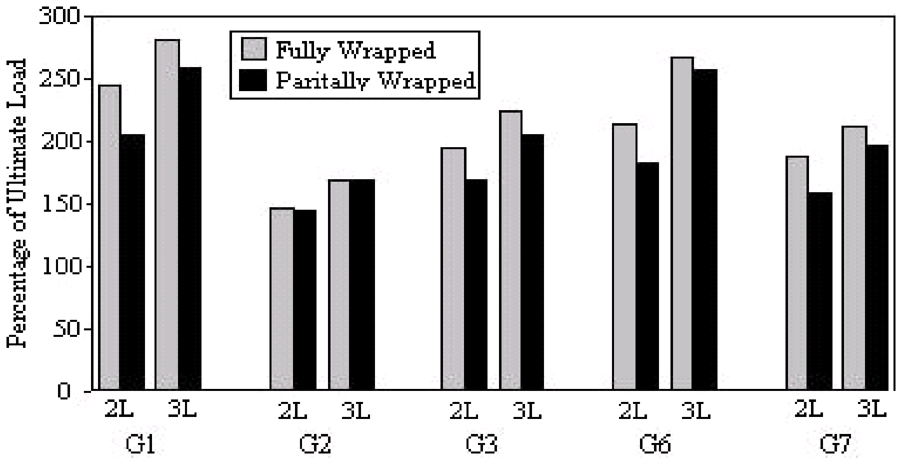


Figure (9) Variation in Percentage of Ultimate Load With CFRP Layers Number [Group (6),(7),(10) and (11) Specimens]



Figure(10) Ultimate Loads for Fully and Partially Wrapped Specimens with 2 and 3 CFRP layers



Figure(11) Percentage of Ultimate Load for Fully and Partially Wrapped Specimens with 2 and 3 CFRP Layers

According to the data of Figure (8), there are no important differences between the percentages of ultimate load for Group (6) and Group (8) specimens, the differences are (1% to 3%). Therefore, reducing the spacing between ties from 70 mm to 40 mm has no effect on the percentages of ultimate load of NSC reinforced specimens with a large amount of main reinforcement and wrapped with CFRP sheets, and slightly affects that of HSC [13% to 30%]. Comparison between results of Figure (5) and (8) indicates that the combined effect of spacing between ties and concrete strength is important only for the concrete reinforced lightly with main bars. Table (4) shows the results of the ultimate load and the percentages for the Group (10) and (11) specimens. Figure (9) shows the variation of percentage of ultimate load for Group (7), (8) , (10) and (11) specimens. Percentages of the ultimate load for NSC specimens are 166% and 239% for one and two layers of CFRP, respectively. For HSC specimens, the percentages are 144% and 167%. Again, the percentages of the ultimate load are higher for NSC. In general, the percentage of the ultimate load is reduced as a result of increase in the height of wrapped reinforced concrete specimens but the change is not large and it ranges between 17% to 25% for NSC and 7% to 21% for HSC specimens. Figure (10) shows the variation of the ultimate load from those specimens partially wrapped and fully wrapped with CFRP sheets. Instead of the outer layer provided in fully wrapped specimens, strips are provided in partially wrapped specimens. Figure (11) shows the variation of the percentages of the ultimate load for partially and fully wrapped specimens. Comparing the two figures indicates the similarity between the two figures leading to a decision that the discussion of the results based on the percentage of the ultimate load (as done in the previous paragraphs) is true for the case of ultimate load capacity of wrapped specimens. Results of Table (2) and Figure (11) indicate that replacing the outer layer in a specimen wrapped with two CFRP layers with strips will reduce the percentages of the ultimate load from 245% to 205% (reduction by 40%). For specimen wrapped with three layers, such replacements lead to reduction from 280% to 258% (reduction by 22%). Different behavior can be observed from HSC specimens of Group (2) that is if the last layer of CFRP is replaced with strips, the percentage of ultimate load is changed by 1% only in one specimen and not changed in the other specimen (remains 168%). Therefore, there is a chance to replace the outer layer of CFRP with strips of CFRP without reducing the ultimate load capacity of HSC, but the change from outer layer to strip lead to reducing the ultimate load by about 22% to 40% in NSC .

3.2 Dilation Ratio of Fiber Wrapped Reinforced Specimens:

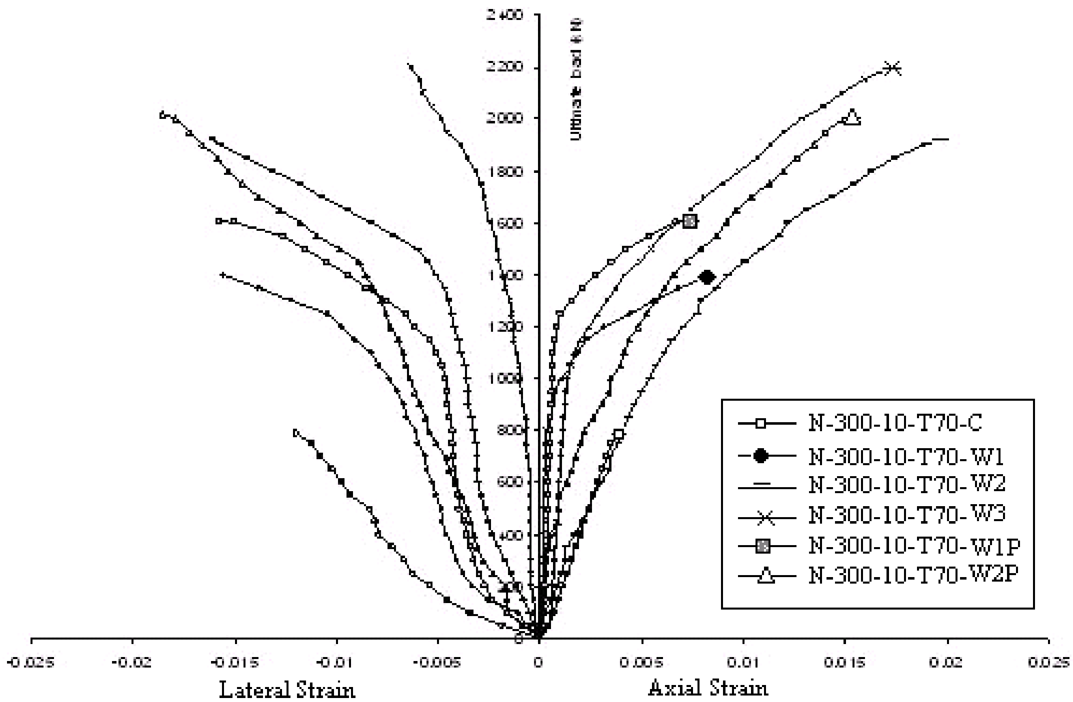
The dilation ratio presents a good indication for the lateral damage that can happen to the column geometry due to access loading. The most important result obtained is the large ratios of dilation for all unwrapped control specimens compared to the wrapped ones indicating the important influence of CFRP wrapping on reducing, to a large extent, the dilation ratios. From the test results data of Tables (3), (4), and (5), one can notice the reduction of dilation ratio as a result of wrapping with CFRP sheets. It is inversely proportional to high confinement; where for almost specimens confined by three layers of CFRP compared to one and two layers wrapping of Group (1), (2), (7) minimum values of dilation ratios were obtained. The same thing can be said for two layers wrapped specimens compared to one layer of Group (4), (8), (9) and (11). With expectance of Group (3), (5), (6) and (10) there was a small difference noticed in the dilation ratio which may be due to improper bonding of CFRP layers and the difference in the readings of dial gauges.

3.3 Load-Strain Relationships of Wrapped Reinforced Concrete Specimens:

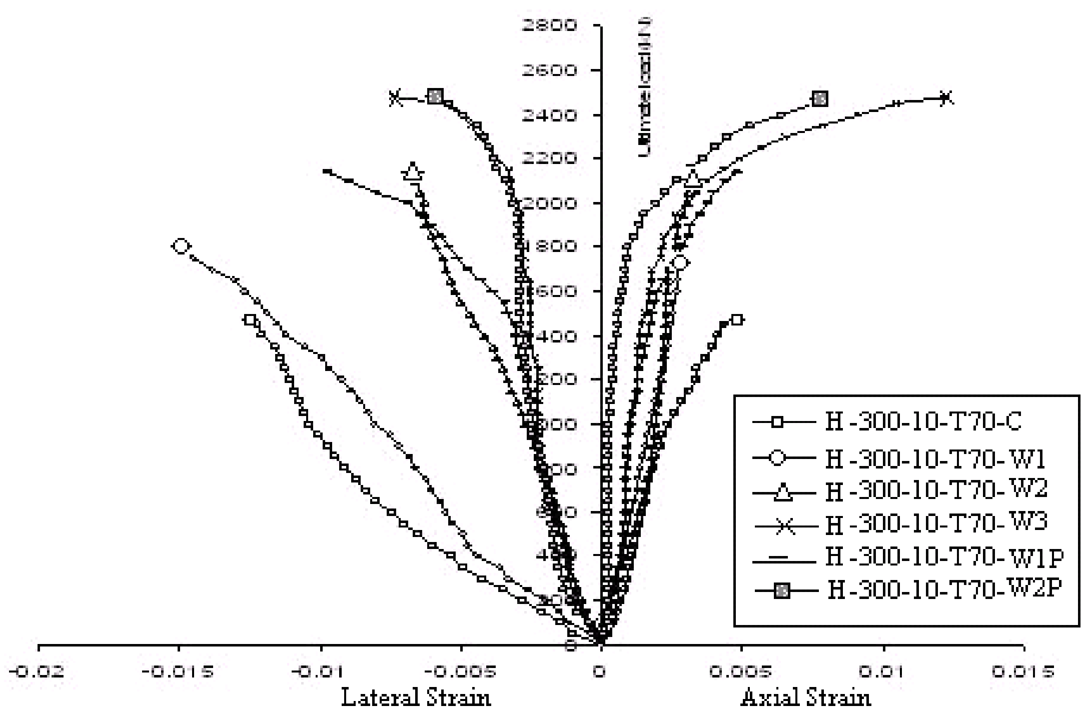
Figures (12) through (22) show the compressive load – axial strain and lateral strain relationships obtained from tests for all groups of specimens. From Figure (12) one can find that replacing the outer layer of CFRP with strips does not affect the maximum axial and lateral strains compared with improving the ultimate load capacity. Comparison between Figure (12) and (13) indicates that both the maximum axial and lateral deformations are in general lower for HSC specimens compared with NSC ones. Nearly, the same observation can be noticed in Figure (17) and (18) specimens [Group (6) and Group (7)] indicating that there is no significant influence of main longitudinal bars on such behavior. The difference between the two maximum deformations as affected by the concrete compressive strength particularly can be considered as another property of the confined concrete. Such property can be added to another properties of concrete confined with FRP sheets that does not change with the existence of main longitudinal steel bars. With regard to the effect of specimen height, it is shown from the comparison between Figure (21) and Figure (17) and between (22) and (18) that changing the specimen height does not affect the axial deformation but it considerably influences the lateral deformation and the role of compressive strength on such properties is not important.

3.4 Modes of Failure:

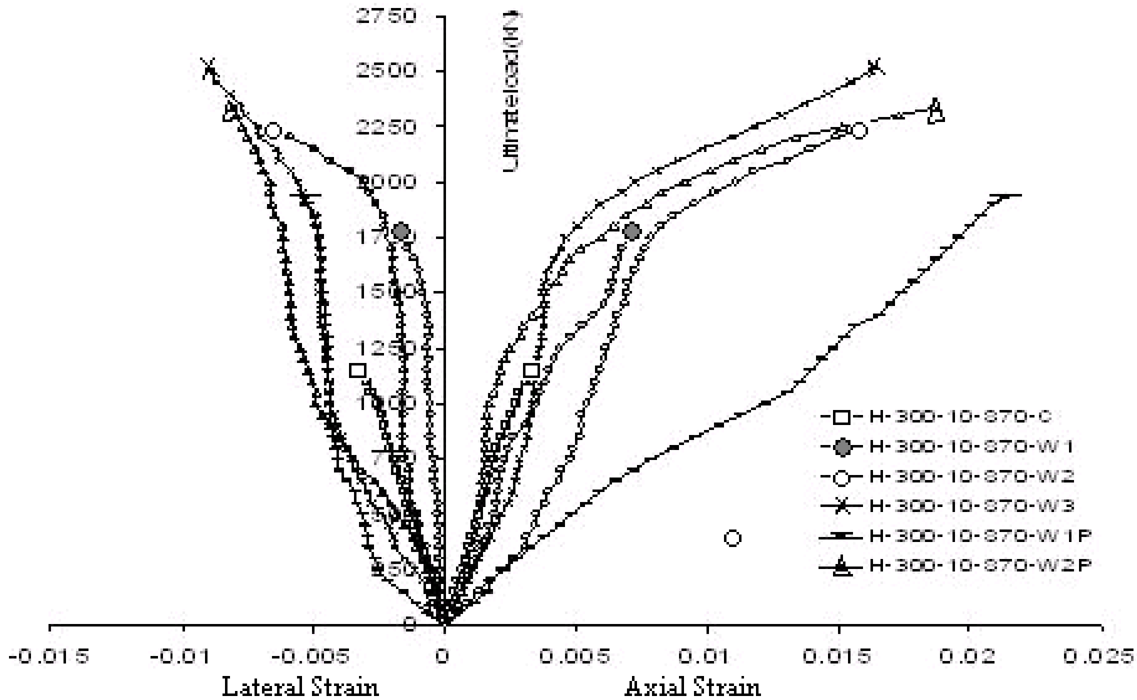
The failure pattern of HSC specimens is governed by an explosive and sudden failure manner accompanied by well crushing of concrete after rupturing the CFRP sheets. Figure(23) show a view of the failure modes for some of tested specimens. For specimens with high number of CFRP layers (two layers and strips, and three layers), well damaged specimens with extensive fractures are observed associated with local buckling of the longitudinal bars and damage of the ties and spirals of Groups (1), (2) and (3). However, this phenomenon is less observed in the case of heavy reinforced specimens of Groups (6) and (7). In low ratios of confinement by CFRP wraps (one layer), light to medium crushing of concrete was observed. In the case of Group (3) with spiral lateral reinforcement, the damaged specimens are noticed by separating the outer layer of concrete cover bonded with CFRP wraps from the inner core of concrete. For specimens with small ties spacing of Groups (4) and (5), the rapture of CFRP and crushing of concrete can be defined within 14- 18 cm at the middle part and the appearance of steel is noticed. This is not the case in the higher steel ratios of Groups (8) and (9) where smaller failure areas were observed with light concrete crushing. Also in specimens with strips the failure areas are concentrated at areas between the strips as weak zones.



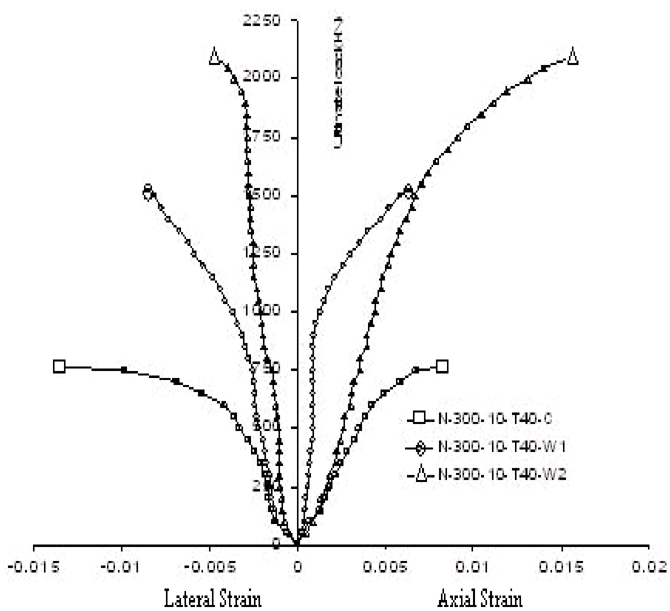
Figure(12) Load-Axial Strain and Lateral Strain Relationships for Group(1) Specimens



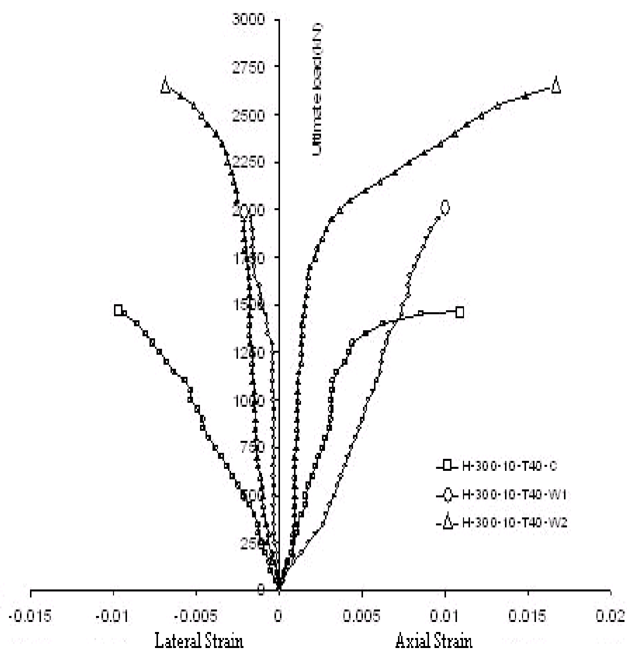
Figure(13) Load-Axial Strain and Lateral Strain Relationships of Group(2) Specimens



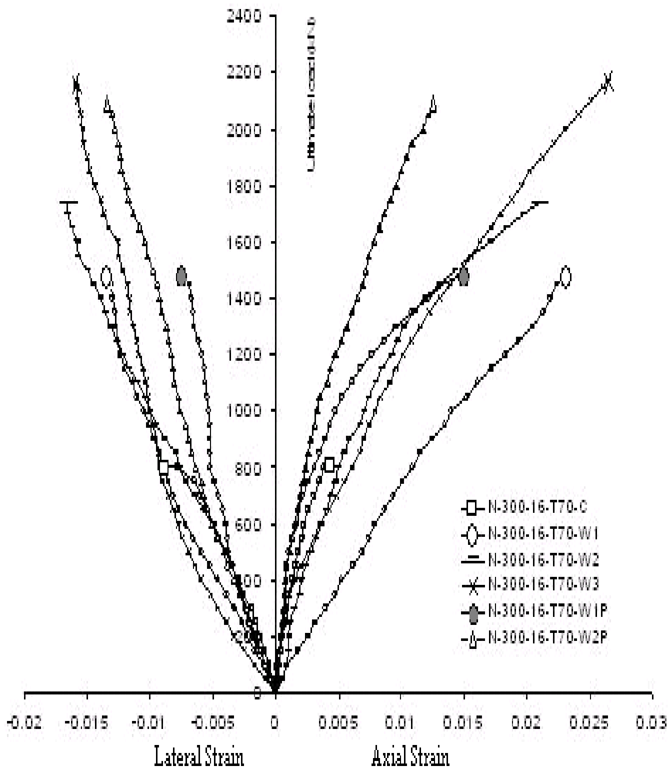
Figure(14) Load-Axial Strain and Lateral Strain Relationships of Group (3) Specimens



Figure(15) Load -Axial Strain and Lateral Strain Relationships of Group (4) Specimens



Figure(16) Load-Axial Strain and Lateral Strain Relationships of Group(5) Specimens



Figure(17) Load-Axial Strain and Lateral Strain Relationships of Group (6) Specimens

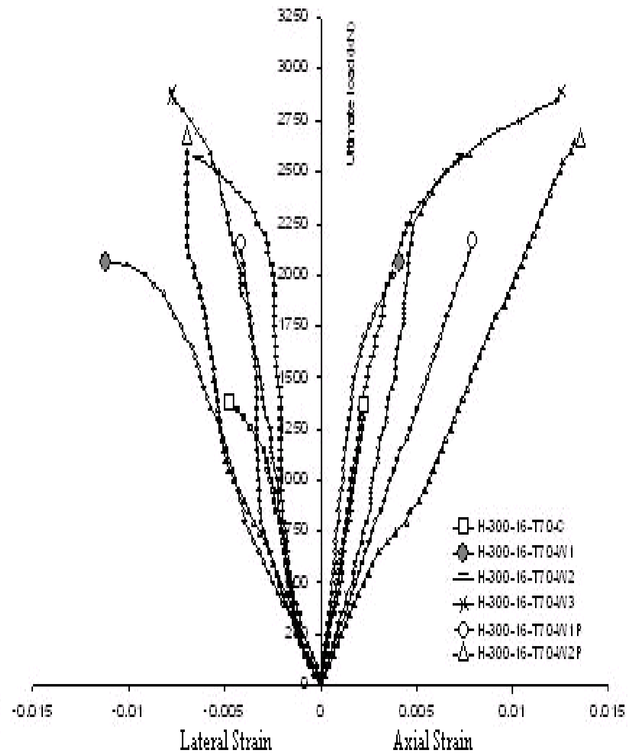


Figure (18) load-Axial Strain and Lateral Strain Relationships of Group (7) Specimens

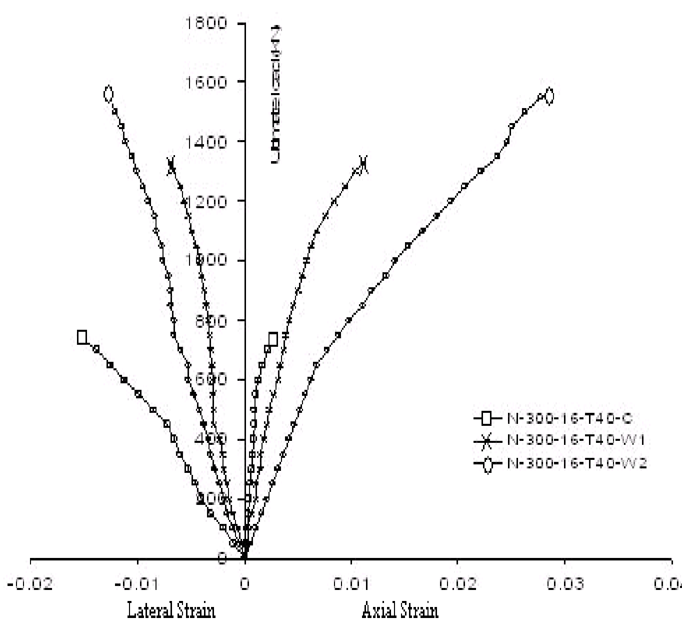
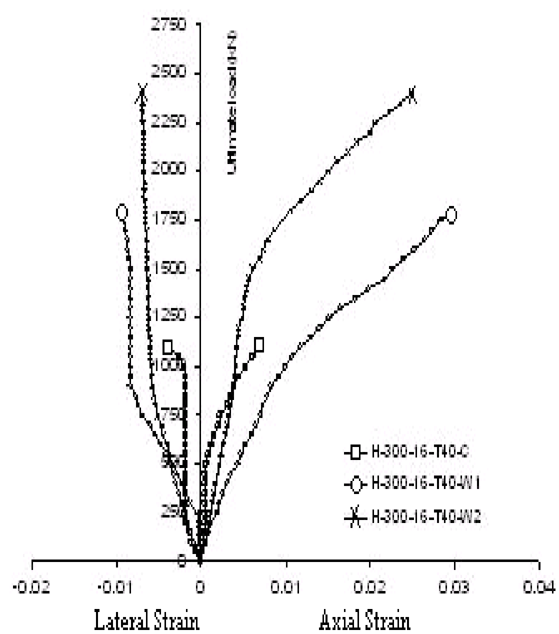
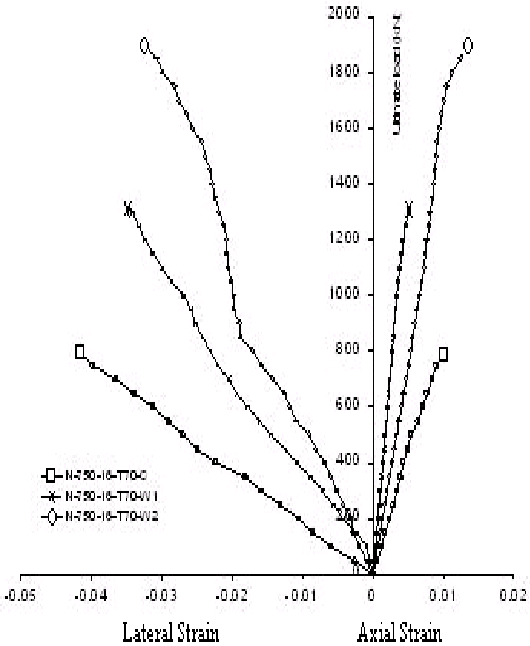


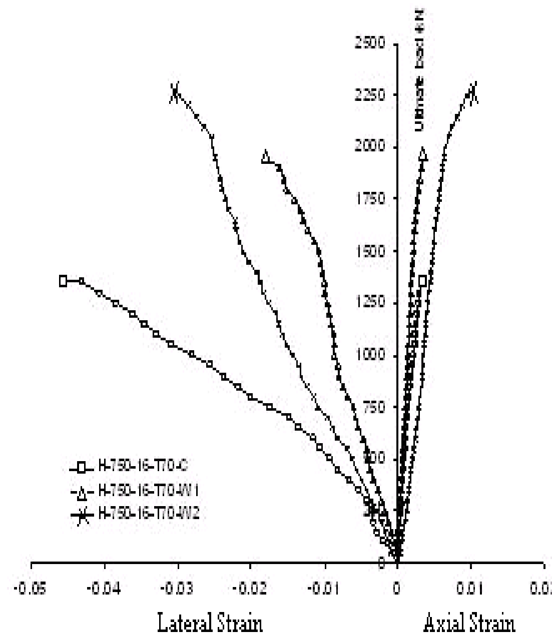
Figure (19) Load -Axial Strain and Lateral Strain Relationships of Group (8) Specimens



Figure(20) Load-Axial Strain and Lateral Strain Relationships of Group(9) Specimens



Figure(21) Load-Axial Strain and Lateral Strain Relationships of Group(10) Specimens



Figure(22)Load-Axial Strain and Lateral Strain Relationships of Group(11) Specimens

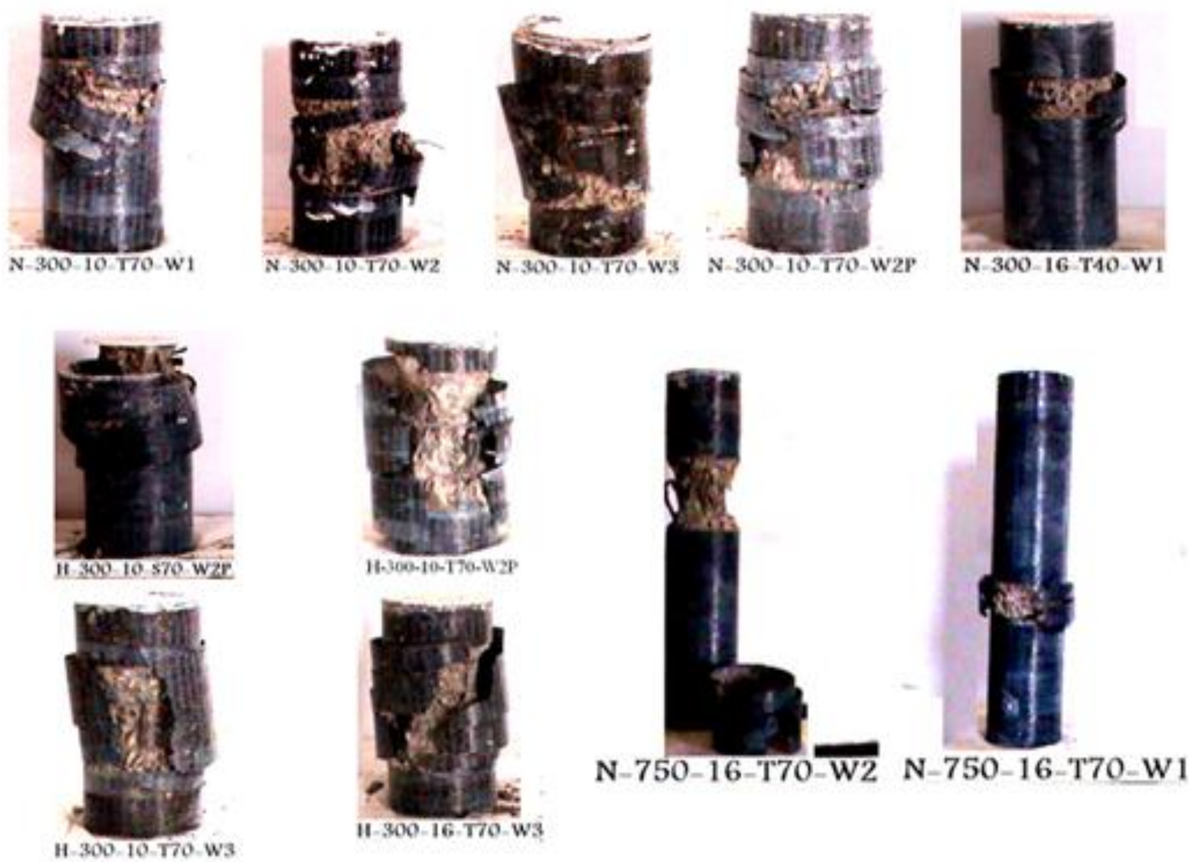


Figure (23) View of Failure pattern and fracture of some specimens

4-Analsis and Modeling

An attempt was made to provide an analytical model for calculating the compressive load-strain relationship of the reinforced concrete confined with CFRP sheets. For this purpose, some models proposed earlier were adjusted to include the effect of axial and lateral reinforcement in addition to the effect of confinement on concrete strength. Parameters of peak compressive stress and ultimate compressive strength and their corresponding strains were calculated for constructing the whole load-strain relationship. Accordingly, the load-strain relationship for the case of short reinforced concrete column wrapped with CFRP can be obtained.

4.1 Basic Properties of CFRP

Based on the test results of tensile stress and deformation of composite CFRP- epoxy material obtained by *Zangana* [20], the properties of different layers of CFRP are shown in Table (5), such properties are used later in the analysis of the reinforced concrete confined by CFRP wraps. Note that both the tensile strength and elastic modulus are reduced with the increase in layers number of CFRP sheets because of the increase in the amount of the epoxy adhesive of lower strength and elastic modulus compared with CFRP material.

Table (5) Basic Properties of Composite CFRP –Epoxy Laminate obtained from *Zangana* [20]

No. of layer	Thickness (mm)	Tensile strength (MPa)	Elastic Modulus (MPa)	Fracture Strain (mm / m)
1	1.4	686	195700	3.51
2	2	590	140125	4.21
3	2.7	520	53900	9.65

4.2 Idealized Form of Stress- Strain Relationship

Different forms of idealized stress-strain relationship were used by researchers. In this analytical procedure the well-known relationship given by *Hognestad* [7] to describe the ascending portion of stress-strain curve for unconfined concrete of the following form is used

$$f'c = f'cp \left[\frac{2\varepsilon c}{\varepsilon' cp} - \left(\frac{\varepsilon c}{\varepsilon' cp} \right)^2 \right] \quad \text{-- (1)}$$

in which f_c is the composite stress in general and f'_{cp} is the peak compressive stress and ε'_{cp} is the corresponding strain. The parameters of the stress-strain relationship are illustrated in Figure (24).

4-3 Parameters of the First Portion of Stress-Strain Curve

The following relationship proposed by *Richart et al* [14] is considered as the main source for calculating the confined stress of concrete and later used (with modifications) by many researchers for calculating the strength of the concrete confined with steel and FRP composites.

$$f'_{cp} = f'_{co} + k \; f_\ell' \quad \text{-- (2)}$$

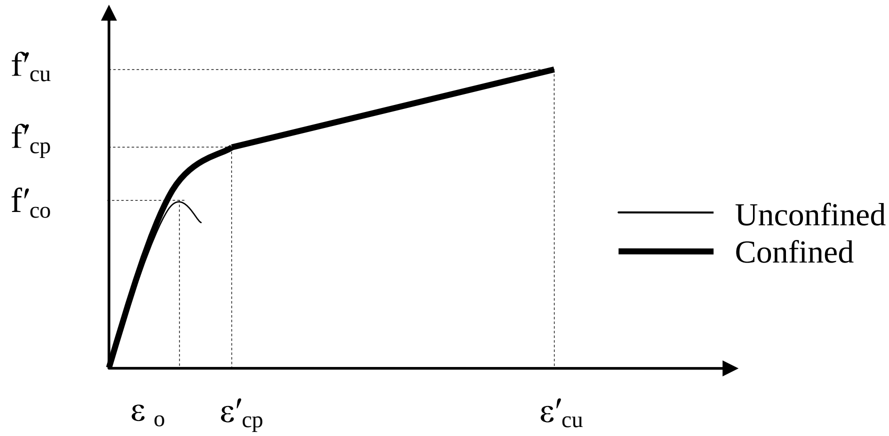


Figure (24) Idealized Form of Stress-Strain Relationship for FRP-Confined Concrete

In which f'_{cp} is the peak compressive stress of the confined concrete, f'_{co} is the compressive stress of the unconfined concrete. f_{ℓ}' is the lateral pressure, k is a constant. For concrete members reinforced with lateral ties or spirals and confined with CFRP sheets Eq.(2) is written as the following form [5]

$$f'cp = f'co + k\left[f_{\ell f} + f_{\ell s}\,\frac{Acc}{Ag}\right] \quad \text{------------ (3)}$$

in which $f_{\ell f}$ and $f_{\ell s}$ are the lateral confining pressure exerted by CFRP wraps and lateral steel reinforcement, respectively. A_{cc} is the area of the confined concrete core and A_g is the gross area of the concrete section. k is the confinement coefficient and in this investigation a value equal to 2.15 proposed by *Lam and Teng* [9] was used. Considering the linear stress-strain response of CFRP, the confinement strength due to the CFRP wrap $f_{\ell f}$ can be represented by the following equation

$$f_{\ell f} = f_{\ell ff} + f_{\ell fp} \quad \text{------------ (4)}$$

where

$$f_{\ell ff} = \frac{1}{2}\,\rho_{ff}\,f_{ff} \quad \text{------------ (5)}$$

and

$$f_{\ell fp} = \frac{1}{2}\,\rho_{fp}\,f_{fp} \quad \text{------------ (6)}$$

in which $f_{\ell ff}$ and $f_{\ell fp}$ are the confinement strength of the fully and partially wrapped concrete, respectively. The value of f_f given is the tensile stress in CFRP. f_{ff} and f_{fp} are the tensile strength of fully and partially wraps of CFRP sheets. ρ_{ff} is the volumetric ratio of CFRP to concrete for fully confined specimen. For one layer of CFRP ρ_{ff} is given by the following form [17]

$$\rho_{ff} = \frac{4\,tff}{D} \quad \text{------------ (7)}$$

For partially wrapped circular concrete members ρ_{fp} is given by

$$\rho_{fp} = \frac{4\,tfp\,bf}{D(bf+sf)} \quad \text{------------ (8)}$$

Lateral confinement pressure due to lateral steel, hoop or spiral $f_{\ell s}$ can be calculated as follows [5]

$$f_{\ell s} = \frac{k_{es}\ k_v\ \rho_{s\ell}\ f_{y\ell}}{2} \qquad (9)$$

For circular hoop

$$\rho_{s\ell} = \frac{\pi\, d}{s} \left(\frac{d_b}{D}\right)^2 . \qquad (10)$$

For rectangular ties

$$\rho_{s\ell} = \frac{2\,(x+y)}{s} \left(\frac{d_b}{D}\right)^2 \qquad (11)$$

in which d is the diameter of concrete core confined by transverse steel reinforcement, D is the diameter of concrete section, d_b and s are the diameter of transverse steel bar and the spacing between them, respectively. For circular confined sections a value of k_{es} is constant and kept to be equal to 1.0 while k_v can be calculated as follows [5]

For circular hoops confinement

$$k_v = \frac{\left(1 - \frac{s}{2\, d_s}\right)^2}{1 - \rho_{cc}} \qquad (12)$$

For concrete confined with spirals

$$k_v = \frac{\left(1 - \frac{s}{2\, d_s}\right)}{1 - \rho_{cc}} \qquad (13)$$

For rectangular ties confinement

$$k_v = \frac{\left(1 - \frac{s}{2\,x}\right)\left(1 - \frac{s}{2y}\right)}{1 - \rho_{cc}} \qquad (14)$$

in which ρ_{cc} is the steel ratio relative to the confined concrete core measured to the outside of hoop, x and y are the larger and smaller dimensions of rectangular steel hoops, respectively.

For calculating the strain at peak confined stress (f'_{cp}), ε'_{cp} the relationship given by Toutanji [17] of the following form is used

$$\varepsilon'_{cp} = \varepsilon_o \left[1 + \left(310.57\, \varepsilon_{\ell o} + \frac{f'_{cp}}{f'_{co}} - 1 \right) \right] \qquad (15)$$

in which $\varepsilon_{\ell o}$ is the yield strain of transverse steel hoop obtained by dividing the yield stress of transverse steel f_{yt} by the elastic modulus of steel or 0.002 if no confinement by steel hoops or spirals are available. ε_o is the strain corresponding to peak compressive stress of unconfined concrete and approximately equal to 0.002 [5]. Equations (3) and (15) then substituted into Eq.(1) for calculating the stress-strain relationship of the first portion of the whole relationship.

4-4 Parameters of the Second Portion of Stress-Strain Curve

As pointed out by many researchers due to the elastic behavior of FRP material till rupture, the second portion of the compressive stress-strain relationship of FRP confined concrete is linear (a straight line) between the peak stress- strain $(f'_{cp} , \varepsilon'_{cp})$ and the ultimate stress-strain $(f'_{cu} , \varepsilon'_{cu})$ points.

For calculating the value of f'_{cu} , a regression analysis was carried out based on the obtained test data. A nonlinear equation of the following form was found to be useful for predicting the dependent variable from the independent variable observations

$$y = a\, e^{b x} \qquad \text{(16)}$$

The dependent variable y is $\dfrac{f'_{cu}}{f'_{co}}$ and the independent variable x is $\dfrac{f_{\ell t}}{f'_{co}}$

Therefore f'_{cu} is equal to

$$f'_{cu} = f'_{co}\ [\, a\ e^{b(f_{\ell t}/f_{co})}\ ] \qquad \text{(17)}$$

Regression analysis was carried out separately for NSC and HSC confined specimens to calculate the constants *a* and *b*. Statistical analysis was carried out using SPSS program to define the most suitable description for the test variable. Figure (25) shows the data distribution and some presentation for linear and nonlinear equations of the data to NSC case and Figure (26) is for the case of HSC.

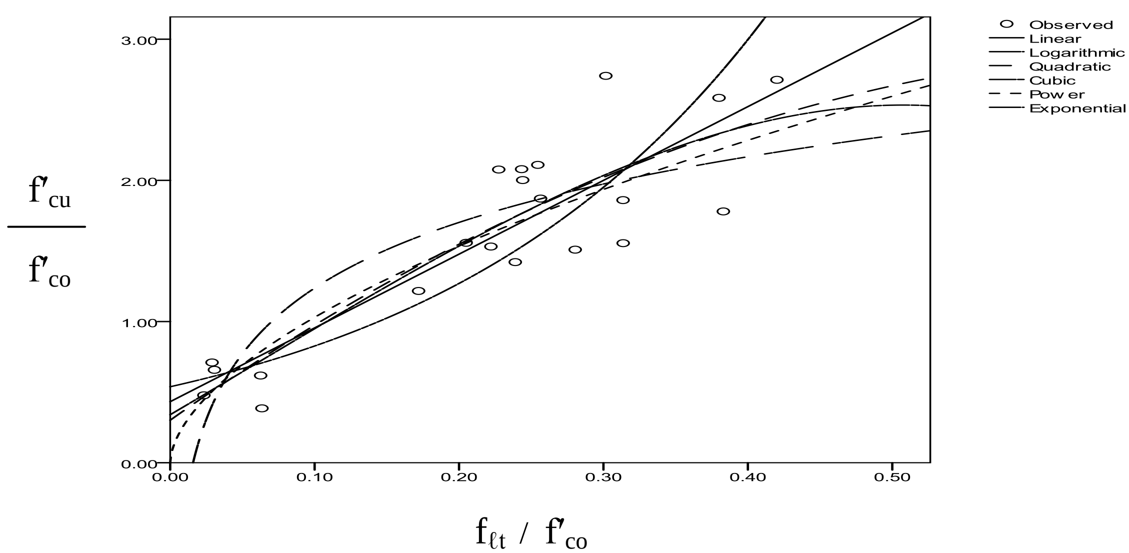


Figure (25) Data Distribution with Some Proposed Relationships for NSC Specimens

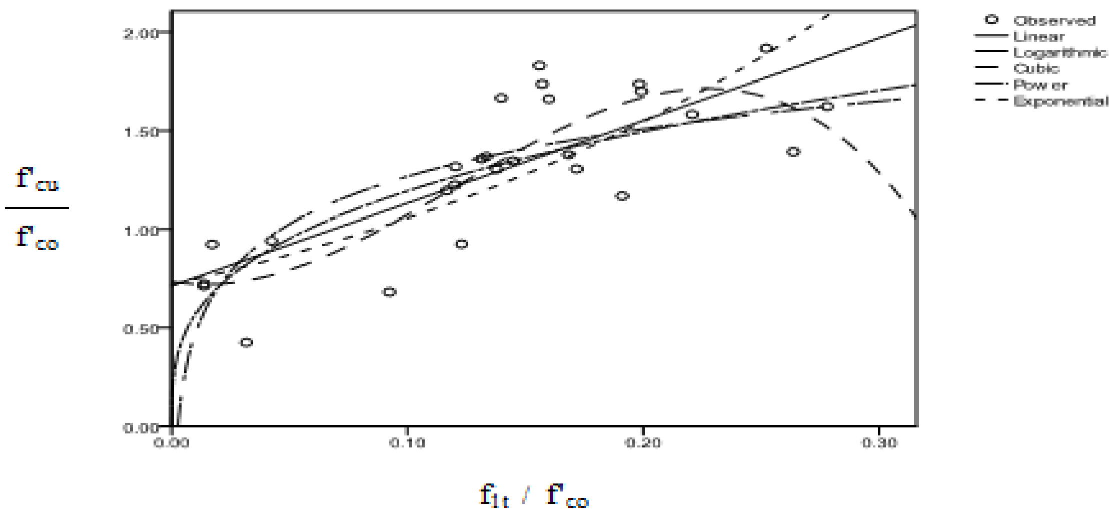


Figure (26) Data Distribution with Some Proposed Relationships for HSC Specimens

Based on the output data of SPSS program the following two equations were obtained to calculate the value of f'_{cu}. Where for the case of NSC the obtained equation has a correlation coefficient equal to 0.89 and given by

$y = 0.53\ e^{4.29\,x}$ --(18)

For the case of HSC the equation has a correlation coefficient equal to 0.835 and has the following form

$y = 0.72\ e^{4.44\,x}$ -- (19)

4.5 Calculation of Load-Strain Relationship

To calculate the ultimate load of the concrete specimens the following relationship is used

$P'_{u,\,cal} = [\ (f'_{cu,\,cal} \times A_c) + P_s\ ]$ --- (20)

where $f'_{cu,\,cal}$ is the ultimate strength calculated by using Eq.(18) and Eq. (19). A_c is the net concrete area of the specimen and it can be calculated as follows

$A_c = A_g - A_s$ --- (21)

where A_s is the area of longitudinal steel bar used, Ø 10 mm or Ø 16 mm, in which P_s is the load carried by steel and can be obtained by using the form

$Ps = fys \times As$ --- (22)

where f_{ys} is the yield stress of the longitudinal bars. By using the value of f'_{cp} calculated from Eq.(3) the peak load is calculated by the following equation

$P'_{cp,\,cal} = (f'_{cp} \times A_c) + Ps$ --- (23)

The following equation proposed by *Wu et al* [18] was used to calculate the ultimate strain $\varepsilon'_{cu,\,cal}$

Table (6) Calculated Compressive Stress, Compressive Strain and Ultimate Load of CFRP Confined Concrete

Group No.	Specimen	$f_{\ell t}$	f'_{cp}	ε'_{cp}	$f'_{cu,\,cal}$	$\varepsilon'_{cu,\,cal}$	P s	P′cp, cal	Pu, cal	Pu, test / Pu, cal
Group (1)	1	1.343	48.212	0.0022	27.818	0.00563	201.592	1075.53	705.65	1.11
	2	8.925	61.713	0.0042	55.603	0.00984	201.592	1320.40	1209.6	1.158
	3	10.65	68.745	0.0046	65.897	0.01038	201.592	1447.92	1396.3	1.376
	4	12.42	66.891	0.0054	79.644	0.01216	201.592	1414.30	1645.6	1.335
	5	13.38	70.439	0.0055	86.853	0.01232	201.592	1478.64	1776.3	0.903
	6	15.11	71.262	0.0064	107.65	0.01403	201.592	1493.58	2153.6	0.937
Group (2)	7	1.343	79.868	0.0021	59.131	0.00544	201.592	1649.66	1273.6	1.158
	8	8.925	92.445	0.0033	83.261	0.00846	201.592	1877.77	1711.2	1.056
	9	10.65	103.03	0.0035	94.906	0.00879	201.592	2069.79	1922.4	1.116
	10	12.42	103.40	0.0038	101.31	0.00962	201.592	2076.54	2038.6	1.217
	11	13.38	107.32	0.0039	107.06	0.00987	201.592	2147.67	2142.9	0.998
	12	15.11	107.42	0.0043	114.89	0.01077	201.592	2149.51	2285	1.086
Group (3)	13	7.220	88.194	0.0027	78.852	0.00715	201.592	1800.67	1631.2	0.701
	14	14.67	102.93	0.0039	112.71	0.01004	201.592	2068.05	2245.4	0.795
	15	16.01	101.91	0.0042	119.21	0.01091	201.592	2049.45	2363.3	0.944
	16	17.49	102.11	0.0046	128.40	0.01183	201.592	2053.06	2530	0.996
	17	18.53	105.23	0.0047	135.95	0.01217	201.592	2109.66	2666.8	0.724
	18	20.63	113.38	0.0049	151.54	0.01259	201.592	2257.45	2949.7	0.791
Group (4)	19	3.232	56.093	0.0024	35.788	0.00643	201.592	1218.46	850.2	0.903
	20	10.81	69.474	0.0043	66.917	0.01025	201.592	1461.15	1414.8	1.074
	21	12.54	76.074	0.0046	77.628	0.01076	201.592	1580.85	1609	1.303
Group (5)	22	3.232	80.682	0.0023	63.569	0.00618	201.592	1664.42	1354.1	1.085
	23	10.81	99.266	0.0034	94.071	0.00898	201.592	2001.48	1907.3	1.054
	24	12.54	104.36	0.0037	103.01	0.00954	201.59	2093.97	2069.5	1.281
Group (6)	25	1.032	34.533	0.0021	20.381	0.00567	427.37	1052.88	796.21	1.02
	26	8.614	67.202	0.0039	55.521	0.00905	427.37	1645.40	1433.5	1.036
	27	10.34	61.194	0.0048	64.262	0.01107	427.37	1536.42	1592.1	1.091
	28	12.11	72.244	0.0049	75.189	0.01103	427.37	1736.84	1790.3	1.211
	29	13.07	60.84	0.0063	93.565	0.01410	427.37	1530.00	2123.5	0.697
	30	14.80	65.679	0.0068	113.28	0.01499	427.37	1617.77	2481.1	0.841
Group (7)	31	1.032	75.391	0.0020	55.811	0.00534	427.37	1793.91	1438.8	0.947
	32	8.614	88.654	0.0033	80.267	0.00847	427.37	2034.47	1882.4	1.096
	33	10.34	94.911	0.0035	89.427	0.00903	427.37	2147.93	2048.5	1.253
	34	12.11	102.34	0.0037	99.781	0.00951	427.37	2282.82	2236.3	1.293
	35	13.07	102.88	0.0039	103.83	0.00997	427.37	2292.63	2309.9	0.932
	36	14.80	105.12	0.0042	112.65	0.01075	427.37	2333.22	2469.7	1.084
Group (8)	37	2.883	47.671	0.0021	31.599	0.00631	427.37	1291.16	999.68	0.737
	38	10.46	51.941	0.0048	67.917	0.01224	427.37	1368.59	1658.4	0.801
	39	12.19	65.804	0.0046	76.784	0.01149	427.37	1620.03	1819.2	0.861
Group (9)	40	2.883	93.372	0.0021	72.949	0.00586	427.37	2120.02	1749.6	0.626
	41	10.46	103.72	0.0032	96.448	0.00854	427.37	2307.79	2175.8	0.824
	42	12.19	106.62	0.0034	103.74	0.00918	427.37	2360.46	2308.2	1.038

Table (6) Continue										
Group No.	**Specimen**	**$f_{\ell t}$**	**f'_{cp}**	**ε'_{cp}**	**$f'_{cu, cal}$**	**$\varepsilon'_{cu, cal}$**	**P s**	**P′cp, cal**	**Pu, cal**	**Pu, test / Pu, cal**
Group (10)	43	1.032	45.077	0.00210	25.929	0.00549	427.37	1244.121	896.85	0.885
	44	8.614	53.171	0.00465	53.261	0.01066	427.37	1390.911	1392.6	0.945
	45	10.34	63.242	0.00475	64.028	0.01078	427.37	1573.572	1587.8	1.196
Group (11)	46	1.032	85.965	0.00205	63.309	0.00529	427.37	1985.695	1574.8	0.861
	47	8.614	90.918	0.00329	81.653	0.00836	427.37	2075.528	1907.5	1.026
	48	10.34	98.399	0.00350	91.429	0.00885	427.37	2211.205	2084.8	1.087

$$\varepsilon'_{cu,\,cal} = \varepsilon_o + \left(1.3 + 6.3\,\frac{f_{\ell t}}{f'_{co}}\right) \quad \text{--} \ (24)$$

Where ε_o is the ultimate strain of unconfined concrete and can be taken equal to 0.0038. From the foregoing calculation steps the complete axial load-deformation relationship can be drawn.

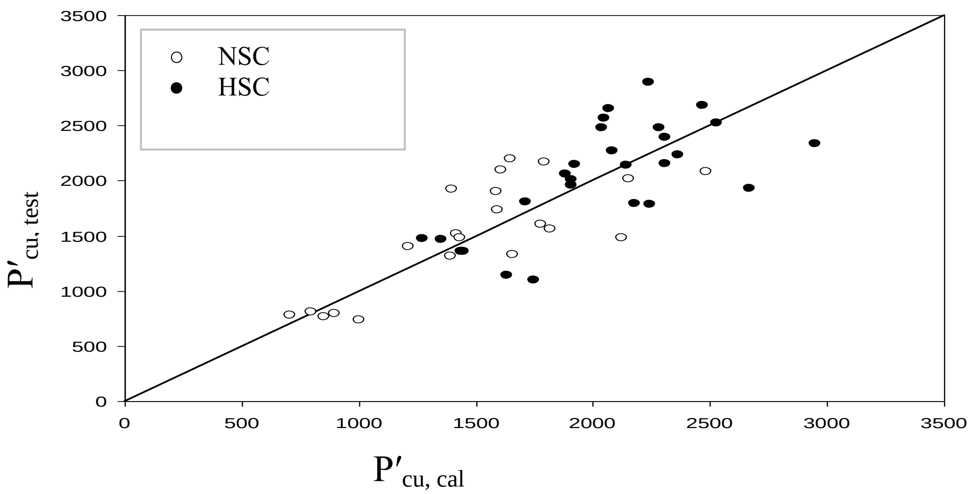
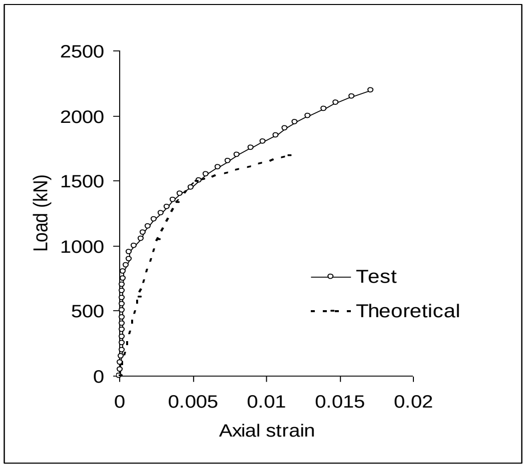
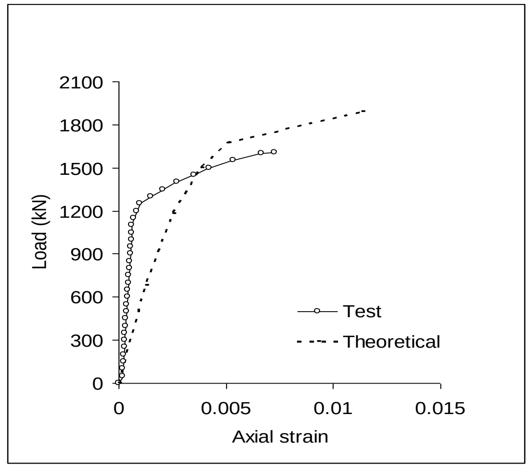


Figure (27) Tested versus Calculated Compressive Axial Load

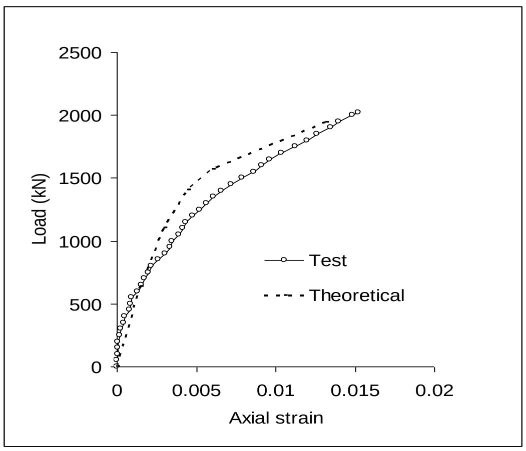
specimens the ratio is equal to 1.0033, indicating the acceptable range of the model predication values.



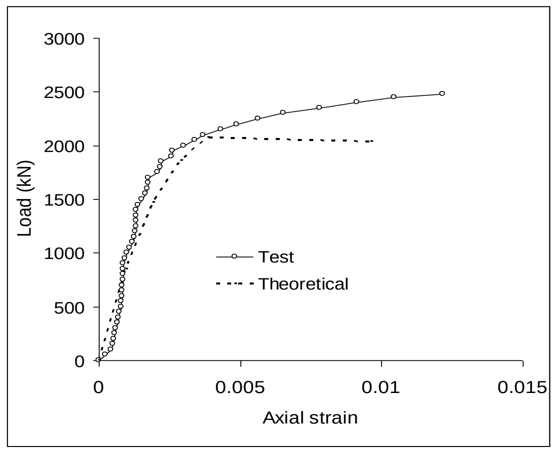
N-300-10-T70-W3



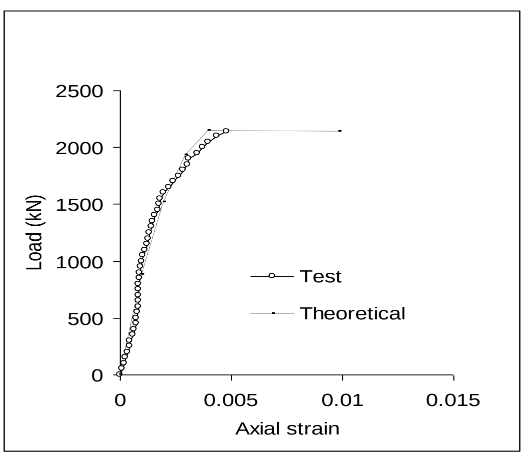
N-300-10-T70-W1P



N-300-10-T70-W2P



H-300-10-T70-W3



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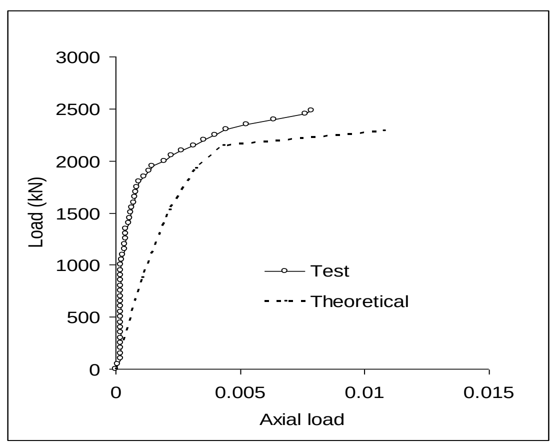

H-300-10-T70-W2P

Figure (28) Tested and Calculated Load-Strain Relationship for Some Tested Specimens

5- Conclusion

From the present research work, the important conclusions may be drawn and summarized as follows

1- As a result of wrapping with CFRP sheets, a state of confinement occurred and accordingly the behavior of concrete becomes different compared with plain concrete. Different ratios in improving the strength characteristics were found for NSC and HSC specimens. The effect of wrapping with CFRP is more clear for the case of NSC.

2- In general, the ratio of ultimate load varied from 123% to 280% and the ultimate load capacity of wrapped specimens varied from 1315.9 kN to 2891.7 kN. Unlike that of NSC specimens a proportional increase in the percentages of ultimate load of HSC with the increase in CFRP layers up to three layers was observed.

3- Change of the ratio of the main bars from 0.0259 to 0.044 has less effect on the percentages of ultimate load capacity of wrapped NSC specimens. Oppositely, the effect is noticeable in HSC specimens where the performance is improved with a ratio varied from 13 % to 44% compared to a ratio equal to 1 % to 31% for NSC. The effect of reducing ties spacing only important in the case of confined HSC specimens. There is an increase in the percentage of ultimate load varied from 23% to 55% as a result of using spiral instead of ties in the HSC specimens. The difference in the ultimate load capacity of wrapped concrete with CFRP between HSC and NSC was found to reduce when the amount of main bars are increased.

4- The role of changing the height of concrete member on the ultimate load capacity after wrapping with CFRP is not significant. The change of the specimen height does not affect the axial deformation but influences the lateral deformation and the dilation ratio.

5- Replacing the outer layer in the specimen wrapped with CFRP layers with strips will reduce the percentages of ultimate load for NSC with ratios varied from 22% to 40% and no reduction was found for HSC specimens.

6- The ductility of the wrapped specimens was improved as a result of strengthening with CFRP sheets, where the behavior changes to more ductile behavior. The comparison of the load-deformation relationships indicated that both the maximum axial and lateral deformations are in general lower for HSC specimens compared with NSC and the influence of main reinforcement on such behavior is not important.

7- An analytical model was proposed for calculating ultimate load capacity and load-strain relationship for reinforced NSC and HSC confined with CFRP sheets. The model predictions were found to be reasonably accurate, and the ratio of test / calculated ultimate load was found to be 1.0043 for NSC and 1.0033 for HSC.

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