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A REVIEW ON BEHAVIOR OF SLENDER RC COLUMNS UNDER AXIAL COMPRESSION AND THEIR STRENGTHENING WITH FRP

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الملخص العربى :

أدت التطورات السريعة في الهندسة المعمارية إلى إدخال المزيد من المباني الشاهقة في العالم مقارنة بالماضي والتي تضع التحديات أمام تصميم أكثر للعناصر النحيفة مثل اعمدة الخرسانة المسلحة النحيفة. يجب زيادة قدرة التحمل لتلك الاعمدة الخرسانية المسلحة النحيفة من اجل ان تفى بوظائف الهيكل المتغيرة. لقد أثبتت تقوية أعمدة الخرسانة المسلحة بالتغليف باستخدام البوليمرات المقواه بالالياف فعاليتها في تحسين السلوك وقدرات التحمل لأعمدة الخرسانة المسلحة القصيرة. كانت معظم الأبحاث السابقة وإرشادات التعزيز حول دراسة أعمدة الخرسانة المسلحة القصيرة و بالتالى ، فإن سلوك أعمدة الخرسانة المسلحة النحيفة و ارشادات التعزيز تحتاج لمزيد من الفهم. في ورقة المراجعة هذه ، تمت مراجعة سلوك أعمدة الخرسانة المسلحة النحيفة الغير مدعمة و المدعمة باستخدام البوليمرات المقواه بالالياف من الأوراق البحثية السابقة. من خلال مراجعة الدراسات المختلفة ، يمكن استنتاج أن نحافة الأعمدة يمكن أن تؤثرعلى طريقة انهيارها و قدرة تحملها للاحمال و الانفاعالات و التشوهات. نسبة نحافة الاعمدة الخرسانية المسلحة هى أيضا احد العناصر التى تؤثر على كفاءة التدعيم.

الكلمات المفتاحية: أعمدة الخرسانة المسلحة, نسبة النحافة, تدعيم, البوليمرات المقواه بالالياف, القدرة الاستعابية للتحميل, الانفاعالات, الانحراف الجانبى, الانحناء, عدم الاتزان.

Abstract:

Rapid architecture developments have introduced more tall buildings in the world compared to the past and that challenge the design of more slender members such as RC slender columns. The load carrying capacities for these slender RC columns need to be increased in order to fulfill the changing structure functions. Strengthening RC columns with FRP wraps has proven its effectiveness in improving the behavior and load carrying capacities for short RC columns. Most of the previous researches and strengthening guidance were more in studying short RC columns; consequently, the behavior of slender RC columns and strengthening guidance need to be more understood. In this review paper, behavior of unconfined and FRP confined slender RC columns and are reviewed from previous research papers. From review various studies, it can be concluded that slenderness of the columns can affect their failure modes, load carrying capacities, strains and deformations. Slenderness ratio is also one of the parameters that affect the strengthening efficiency of RC columns.

Keywords: RC columns, Slenderness ratio, strengthening, FRP, load carrying capacity, strain, Lateral deflection, buckling, instability.

1. Introduction

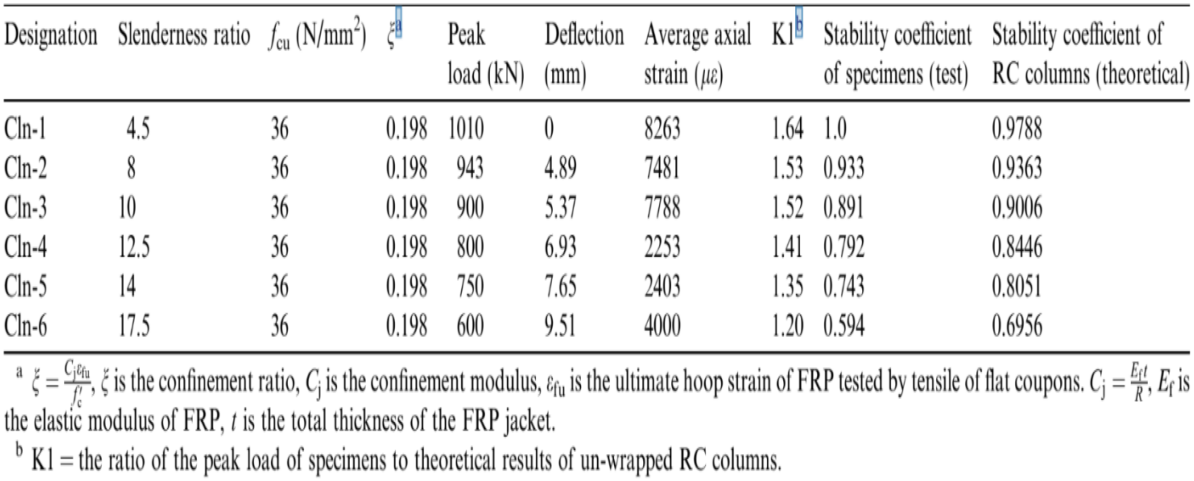
A column is a structure member under axial compression, however; most column members, in reality, are subjected to bending moment in addition to the axial compression and that can arise from material or geometric imperfections.

Columns are divided into two categories short and slender columns depending on their slenderness ratios. Slenderness ratio is one of the important parameters that affect the behavior of RC columns. Slenderness ratio is ($\lambda = kL/r$), where k and L are the column effective length factor and the unsupported length of the column, respectively; and r is the radius of gyration of the column section. For short columns with lower slenderness ratios, the stiffness and flexure rigidity is relatively high, columns are only subjected to first order moment effect which is insignificant and can be declined while, slender columns with high slenderness ratios experience a reduction in their stiffness and thus, they are vulnerable to large lateral deformations causing secondary order moment effect and instability buckling failure to occur hence, the behavior of slender column is more complicated and must be well understood, and the effect of the additional bending moment exerts on this columns must taken into account in the design consideration. The strengthening of RC structures is critically important to enhance the serviceability and the capacity of structures in response to the increase in load demand beyond the original design. Common strengthening methods such as section enlargement (concrete jacketing), externally bonded steel plates, and externally bonded fiber-reinforced polymer (FRP) have been used for many years to improve structural service performance and ultimate capacity of concrete structures. FRP composites are characterized by their high strength to weight ratio and their corrosion resistance that results in a significant increase in using them in various civil engineering applications. FRP have proven their effectiveness in strengthening of RC columns since they are able to enhance the load carrying capacity and strains of concrete. The available strengthening guidelines are more for short columns than slender ones which make the behavior of strengthened slender RC columns is confusing and need to be more understood.

2. Literature review

Pan, J. L. et al. [6] tested six rectangular RC columns wrapped with FRP under axial compression. The rectangular cross-section of the specimens was (120×150) mm, the slenderness ratio (L/b) was 4.5, 8, 10, 12.5, 14, and 17.5 respectively. The FRP was made of high strength unidirectional carbon fibers. The test results for columns are shown in **Table 1**.

Table 1: The test results for columns of **Pan, J. L. et al. [6]**



Designation	Slenderness ratio	f_{cu} (N/mm^2)	ξ [a]	Peak load (kN)	Deflection (mm)	Average axial strain ($\mu\varepsilon$)	K1 [b]	Stability coefficient of specimens (test)	Stability coefficient of RC columns (theoretical)
Cln-1	4.5	36	0.198	1010	0	8263	1.64	1.0	0.9788
Cln-2	8	36	0.198	943	4.89	7481	1.53	0.933	0.9363
Cln-3	10	36	0.198	900	5.37	7788	1.52	0.891	0.9006
Cln-4	12.5	36	0.198	800	6.93	2253	1.41	0.792	0.8446
Cln-5	14	36	0.198	750	7.65	2403	1.35	0.743	0.8051
Cln-6	17.5	36	0.198	600	9.51	4000	1.20	0.594	0.6956

[a] $\xi = \frac{C_j \varepsilon_{fu}}{f'_c}$, ξ is the confinement ratio, C_j is the confinement modulus, ε_{fu} is the ultimate hoop strain of FRP tested by tensile of flat coupons. $C_j = \frac{E_f t}{R}$, E_f is the elastic modulus of FRP, t is the total thickness of the FRP jacket.

[b] K1 = the ratio of the peak load of specimens to theoretical results of un-wrapped RC columns.

They found that the FRP strengthening effect is inversely proportional with the slenderness ratio of the column. For columns with slenderness ratio L/b greater than 10, failure occurred due to buckling and the FRP cannot be used fully due to its rupture after the peak load.

Fitzwilliam, J., & Bisby, L. A. [2] studied the effect of FRP hoop and longitudinal wraps on RC columns with different slenderness ratios. Their study included eighteen circular RC columns with varying slenderness and CFRP strengthening schemes. All columns were 152 mm in diameter and the column lengths were 300 mm, 600 mm, 900 mm, and 1,200 mm and tested to failure under eccentric axial compression. The column slenderness, kL/r, was varied between approximately 10 and 35. They come out that increased slenderness caused decreased load capacity and increased lateral deflection. Slenderness effects were more significant for CFRP wrapped columns with higher levels of CFRP confinement. The effect of slenderness and CFRP wrapping scheme on peak load capacity are shown in **Fig. 1**.

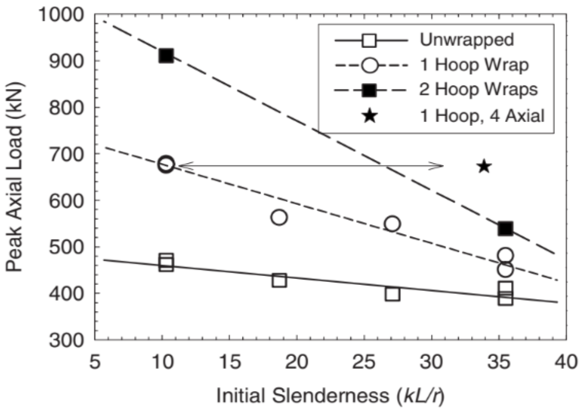
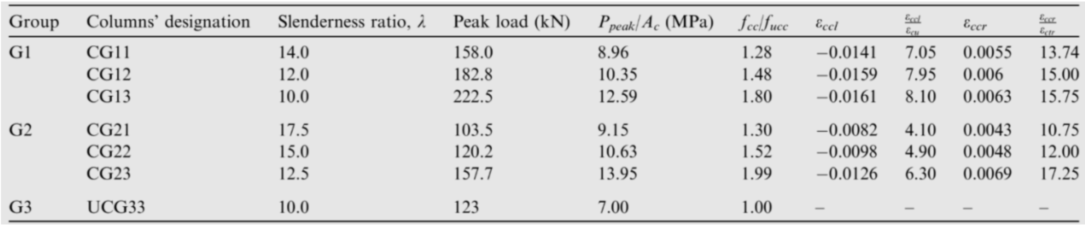


Fig. 1: Effect of slenderness and CFRP wrapping scheme on peak load capacity of **Fitzwilliam, J., & Bisby, L. A. [2]**

Slender member strengthened with hoop wraps only suffered from reduced flexural rigidity leads to instability failure under increasing secondary moments. Longitudinal CFRP wraps can be used improve the behavior of slender CFRP wrapped circular concrete columns and allow them to achieve higher strengths as it contributes significantly to the tangent flexural rigidity of the member at higher loads near ultimate.

Soliman, A. E. K. S. [9] studied confining concrete columns having different slenderness ratios with fiber reinforced plastic/polymer (FRP) and how it affected the compressive strength, failure mode, axial, and radial strains. The study included six filled plastic tube concrete column specimens without steel reinforcement and one unconfined concrete specimen having slenderness ratios ranged from 10 to 17.5. Test results of column specimens are shown in **Table 2**.

Table 2: Test results of column specimens of **Soliman, A. E. K. S. [9]**



Group	Columns' designation	Slenderness ratio, λ	Peak load (kN)	P_{peak}/A_c (MPa)	f_{cc}/f_{ucc}	ε_{ccl}	$\frac{\varepsilon_{ccl}}{\varepsilon_{cu}}$	ε_{ccr}	$\frac{\varepsilon_{ccr}}{\varepsilon_{ctr}}$
G1	CG11	14.0	158.0	8.96	1.28	−0.0141	7.05	0.0055	13.74
	CG12	12.0	182.8	10.35	1.48	−0.0159	7.95	0.006	15.00
	CG13	10.0	222.5	12.59	1.80	−0.0161	8.10	0.0063	15.75
G2	CG21	17.5	103.5	9.15	1.30	−0.0082	4.10	0.0043	10.75
	CG22	15.0	120.2	10.63	1.52	−0.0098	4.90	0.0048	12.00
	CG23	12.5	157.7	13.95	1.99	−0.0126	6.30	0.0069	17.25
G3	UCG33	10.0	123	7.00	1.00	–	–	–	–

He came out that for columns with lower slenderness ratios, the failure mode was noticed to be a diagonal shear failure and the failure of the specimens occurred due to the failure of the plastic tube, while columns with higher slenderness ratios experienced tensile failure due to the excessive increase of the observed horizontal displacements; at mid-height of column specimens, crushing of concrete had occurred on one side while tensile cracks were observed on the other side of the tested sample.

Chikh, N. et al. [1] studied the effect of both slenderness and strengthening ratios for the column specimens confined with CFRP wraps on the ultimate strength, stiffness, and ductility of the specimens. 18 columns specimens having concrete column strength of 25 MPa, slenderness ratios (L/Ø = 2; 5 and 6.5) and strengthened with 0, 1 and 3 layers of CFRP wraps are studied. They concluded that increasing the slenderness of the column led to both a change in the location of failure from its central zone to a lower one and a decrease in the CFRP ruptured, increasing the CFRP strengthening ratio resulted in increasing the compressive strength of the confined columns. For columns having the same cross-section area, increasing the slenderness ratio leads to a small decrease in the load carrying capacity and a moderate reduction in the axial deformation in contrary, this statement is not considered for columns with different cross-sections.

Raval, R., & Dave, U. [8] investigated the axial strain of columns having different cross-section geometry. A total of 15 RC columns of 1 meter in height were cast and loaded to fail in axial compression, 9 columns were control and the rest 6 columns were strengthened with one layer of GFRP wrap having 20mm of corner radius, the compressive strength of RC columns is equal to 15Mpa and the slenderness ratios are 5.8, 6.67 and 9 for circular, square and rectangular column respectively. They found that the effective confinement with GFRP wrapping resulted in improving the compressive strength. GFRP wrapping for circular columns produced highest increment in axial load than square and rectangular columns. Control and GFRP wrapped circular columns undergo higher axial deformation as compared to that for rectangular columns. Also, they observed higher deformation for GFRP wrapped rectangular columns as compared to that for square and circular columns because of slenderness effects have resulted into bending at the time of failure under small eccentricity.

Saravanan, J. et al. [10] studied the effect of the slenderness ratio on the ultimate strength, ductility, axial, and lateral strains on high strength circular RC columns wrapped with UDCGFRP wraps. The study included 12 column specimens having 150 mm diameter, height range from 300 mm to 1200 mm and nominal slenderness ratios ($\gamma = I_{eff}/ r_g$) of 8, 16, 24 and 32; one column for each slenderness ratio was kept as a reference column and was tested without any wrapping, the remaining columns were wrapped with UDCGFRP wraps with used thicknesses 3 and 5 mm. They deduced that, increasing the slenderness ratio results in decreasing the ultimate strength of the column. Increasing the thickness of the fiber used leads to an increase in the ultimate strength. The axial strain and deflection ductility for unwrapped columns showed maximum sensitivity to slenderness ratio than wrapped ones. Ultimate loads, stresses and strains for tested columns are shown in **Table 3**

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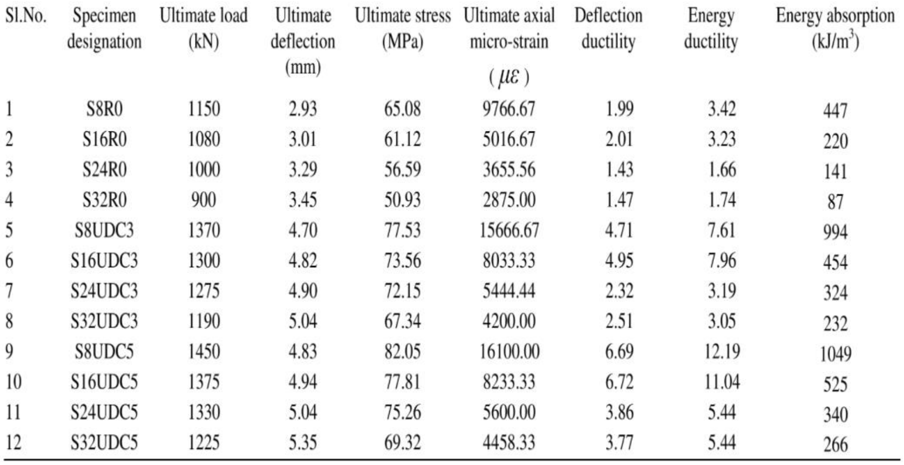
Table 3: Ultimate loads, stresses and strains for tested columns of **Saravanan, J. et al. [10]**



Sl.No.	Specimen designation	Ultimate load (kN)	Ultimate deflection (mm)	Ultimate stress (MPa)	Ultimate axial micro-strain ($\mu\varepsilon$)	Deflection ductility	Energy ductility	Energy absorption (kJ/m^3)
1	S8R0	1150	2.93	65.08	9766.67	1.99	3.42	447
2	S16R0	1080	3.01	61.12	5016.67	2.01	3.23	220
3	S24R0	1000	3.29	56.59	3655.56	1.43	1.66	141
4	S32R0	900	3.45	50.93	2875.00	1.47	1.74	87
5	S8UDC3	1370	4.70	77.53	15666.67	4.71	7.61	994
6	S16UDC3	1300	4.82	73.56	8033.33	4.95	7.96	454
7	S24UDC3	1275	4.90	72.15	5444.44	2.32	3.19	324
8	S32UDC3	1190	5.04	67.34	4200.00	2.51	3.05	232
9	S8UDC5	1450	4.83	82.05	16100.00	6.69	12.19	1049
10	S16UDC5	1375	4.94	77.81	8233.33	6.72	11.04	525
11	S24UDC5	1330	5.04	75.26	5600.00	3.86	5.44	340
12	S32UDC5	1225	5.35	69.32	4458.33	3.77	5.44	266

Parthasarthi, N. et al. [7] tested four high strength reinforced concrete square columns with dimensions 2200x150x150 mm under constant axially and bi-axially loaded conditions. The average compressive strength of concrete cube is equal to 51.2Mpa and the slenderness ratio is equal to 14.6. Details of eccentrically loaded column are shown in **Table 4**. They observed a reduction in the biaxial load capacity as a result of increasing the eccentricity based on the ultimate loads for reinforced concrete column. The reduction in the biaxial load capacity of the columns with high eccentricity was more than that of lower one. In columns having the same eccentricity, the reduction in the biaxial load capacity is more for specimen with higher longitudinal reinforcement ratio. Ultimate loads for the specimen with different eccentric loading and longitudinal reinforcement are shown in **Fig. 2**.

Table 4: Details of eccentrically loaded column of **Parthasarthi, N. et al. [7]**

Specimen details	Longitudinal reinforcement		Eccentricity in mm
	Steel details	Ratio	
Central Axial loading	6Number of 12mm Diameter	μ = 3.01%	0
C1			300mm(2d)
C2			150mm(d)
C3	4Number of 12mm Diameter	μ = 2.01%	300mm(2d)
C4			150mm(d)

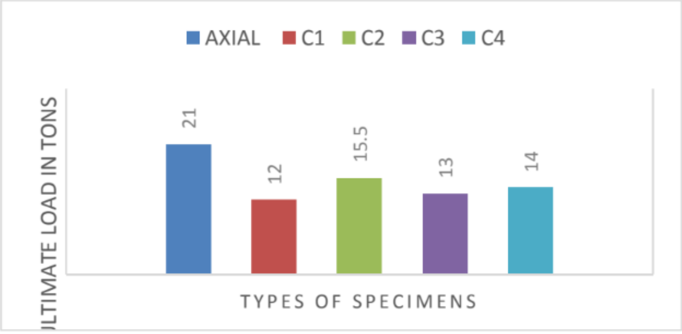


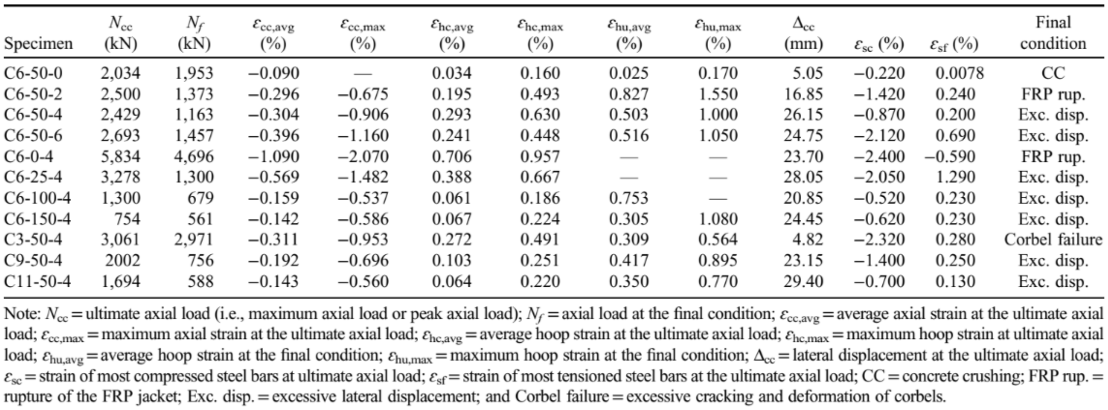
Fig. 2: Ultimate loads for the specimen with different eccentric loading and longitudinal reinforcement of **Parthasarthi, N. et al. [7]**

Maranan, G. B., et al. [4] cast and tested eight full-scale geopolymer-concrete circular columns reinforced longitudinally and transversely with glass-fiber-reinforced-polymer (GFRP) bars under concentric loading. Six short columns (L/r = 8) were cast: one column without transverse reinforcement; three columns with circular hoops spaced at 50 mm, 100 mm, and 200 mm on centers; and two columns with spirals spaced at 50 mm and 100 mm on centers. In addition, two slender columns (L/r = 16) transversely reinforced with hoops and spirals both spaced at 100 mm on centers were fabricated. They noticed that the slender columns exhibited higher deformation compared to the short columns due to their lateral movement, so they failed at a lower load compared to that of short column. The higher average ductility index and average confinement efficiency of the spiral-confined columns lead to more ductile behavior and higher post concrete-cover spalling strength of those columns compared to the hoop-confined ones. GFRP-reinforced geopolymer-concrete system was found to be more compatible than GFRP-RC system due to the higher elastic modulus of geopolymer concrete (33 GPa) compared to normal concrete (29 GPa) of the same grade (38 MPa), resulting in higher normalized strength (97.3%) compared to GFRP-RC circular columns (88.3%).

Montaser, W., et al. [5] tested three groups, each group consists of 5 square RC columns are tested, each column has dimension= 150mm × 150mm and slenderness ratio = 10. Two RC heads were used at ends of each column with dimension of 150 × 450-mm to prevent any stress concentrations. They found that the width of CFRP strips (W) preferred to be equal or more than spacing of CFRP strips (S) to qualify the required capacity. Increasing the CFRP ratio increases the efficiency of stirrups because the failure happens on high load where stirrups reached to maximum strain.

Xing, L. et al. [11] studied behavior of circular RC columns confined with FRP jacketing loaded eccentrically. The study concerned in several parameters that may affect the load carrying capacities and deformability of the confined RC columns; these parameters included the slenderness ratio (Length to diameter ratio of the column (L/D)), number of confining FRP layers and loading eccentricity. 10 RC columns specimens having the same diameter of 300 mm were included in their study; these specimens were divided into three groups to study the effect of each parameter. The noticed that, for all the FRP-confined columns, both the most compressed and the most tensioned longitudinal steel bars yielded before the ultimate axial load was reached. For the unconfined column , failure was sudden and characterized by concrete crushing and spalling near mid height on the compression side. The measured strains of the longitudinal steel bars in this specimen suggest that no yielding of these bars occurred prior to concrete crushing, and very small lateral displacements had developed at failure. The ultimate axial load, moment capacity and axial strain at ultimate load are direct proportional to the FRP thickness and inverse proportional to the initial load eccentricities and slenderness. Increasing the slenderness leads to an increase in the mid-height lateral displacement under the same load. Summary of test results is shown in **Table 5**.

Table 5: Summary of test results of **Xing, L. et al. [11]**



Specimen	N_{cc} (kN)	N_f (kN)	$\varepsilon_{cc,avg}$ (%)	$\varepsilon_{cc,max}$ (%)	$\varepsilon_{hc,avg}$ (%)	$\varepsilon_{hc,max}$ (%)	$\varepsilon_{hu,avg}$ (%)	$\varepsilon_{hu,max}$ (%)	Δ_{cc} (mm)	ε_{sc} (%)	ε_{sf} (%)	Final condition
C6-50-0	2,034	1,953	−0.090	—	0.034	0.160	0.025	0.170	5.05	−0.220	0.0078	CC
C6-50-2	2,500	1,373	−0.296	−0.675	0.195	0.493	0.827	1.550	16.85	−1.420	0.240	FRP rup.
C6-50-4	2,429	1,163	−0.304	−0.906	0.293	0.630	0.503	1.000	26.15	−0.870	0.200	Exc. disp.
C6-50-6	2,693	1,457	−0.396	−1.160	0.241	0.448	0.516	1.050	24.75	−2.120	0.690	Exc. disp.
C6-0-4	5,834	4,696	−1.090	−2.070	0.706	0.957	—	—	23.70	−2.400	−0.590	FRP rup.
C6-25-4	3,278	1,300	−0.569	−1.482	0.388	0.667	—	—	28.05	−2.050	1.290	Exc. disp.
C6-100-4	1,300	679	−0.159	−0.537	0.061	0.186	0.753	—	20.85	−0.520	0.230	Exc. disp.
C6-150-4	754	561	−0.142	−0.586	0.067	0.224	0.305	1.080	24.45	−0.620	0.230	Exc. disp.
C3-50-4	3,061	2,971	−0.311	−0.953	0.272	0.491	0.309	0.564	4.82	−2.320	0.280	Corbel failure
C9-50-4	2002	756	−0.192	−0.696	0.103	0.251	0.417	0.895	23.15	−1.400	0.250	Exc. disp.
C11-50-4	1,694	588	−0.143	−0.560	0.064	0.220	0.350	0.770	29.40	−0.700	0.130	Exc. disp.

Note: N_{cc} = ultimate axial load (i.e., maximum axial load or peak axial load); N_f = axial load at the final condition; $\varepsilon_{cc,avg}$ = average axial strain at the ultimate axial load; $\varepsilon_{cc,max}$ = maximum axial strain at the ultimate axial load; $\varepsilon_{hc,avg}$ = average hoop strain at the ultimate axial load; $\varepsilon_{hc,max}$ = maximum hoop strain at ultimate axial load; $\varepsilon_{hu,avg}$ = average hoop strain at the final condition; $\varepsilon_{hu,max}$ = maximum hoop strain at the final condition; Δ_{cc} = lateral displacement at the ultimate axial load; ε_{sc} = strain of most compressed steel bars at ultimate axial load; ε_{sf} = strain of most tensioned steel bars at the ultimate axial load; CC = concrete crushing; FRP rup. = rupture of the FRP jacket; Exc. disp. = excessive lateral displacement; and Corbel failure = excessive cracking and deformation of corbels.

Hu, Z. et al. [3] studied the effect of slenderness on the behavior of RC columns wrapped with CFRP cloth and loaded concentrically. Their study included a total of 12 columns; half the columns were unwrapped columns, and the other half were wrapped ones, all the columns having a diameter of 200 mm and slenderness ratios (kL/r) of 12, 20, 32, 40, 48, and 56. They concluded that the slenderness ratio can affect the bearing capacity of the columns; by increasing the slenderness ratio of the column, its load carrying capacity decreases. The influence of the slenderness ratio of the columns in reducing the ultimate load capacity is found to be greater for wrapped column than unwrapped ones. Ultimate axial load versus slenderness ratios relationships are shown in **Fig. 3**. As the slenderness ratio of test specimen increases, the circumferential strain (εc) and the vertical strain (εv) of specimens decrease gradually, which indicated that the restraining effect of FRP is declined. By increasing the slenderness ratio of the columns, the lateral deflection of mid-height increased significantly at loads close to the ultimate value. It can be concluded that CFRP circumferential restraint cannot increase the flexural stiffness of the column.

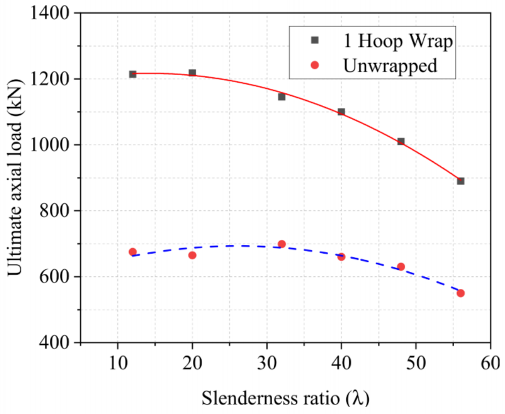


Fig. 3: Ultimate axial load versus slenderness ratios relationships of **Hu, Z. et al. [3]**

3. Conclusions

Following are the results of literature review:

1) As the slenderness ratio of column increases, its ultimate axial load decreases.
2) The effect of FRP strengthening of columns decreases as the slenderness ratio increases.
3) Strengthening slender columns in the hoop direction have insignificant effect on enhancing their flexure stiffness.
4) Strengthening the slender columns in with FRP laminates in the longitudinal direction help in improving their behavior and increasing their strength.
5) Slenderness effects were more significant for CFRP wrapped columns with higher levels of CFRP confinement.
6) As the slenderness ratio of the column increases, the lateral deflection increases.
7) Increasing the FRP thickness leads to increasing the ultimate axial load, moment capacity and axial strain at ultimate load for confined columns.
8) Increasing the initial load eccentricity for columns results in decreasing the ultimate axial load, moment capacity and axial strain at ultimate load.

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