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PREDICTION OF AXIAL COMPRESSIVE STRENGTH OF HYBRID. REIN FORCED CONCRETE COLUMNS UNDER STATIC LOADING

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Abstract:
Especially in the marine environment, steel corrosion is one of the main factors for the insufficient durability of concrete structures. Therefore, using Fiber-Reinforced polymer (FRP) bars in aggressive environments has become of tremendous interest to avoid corrosion problems in addition to its attractive mechanical characteristics. However, the behavior of fiber-reinforced polymer (FRP) bars under compression is not fully understood yet due to the limited researches in this area. The objective of this work is to study the behaviorto predict the axial compressive strength of columns when replacing steel reinforcement with hybrid one. Hybrid bars are steel ones that have been steel bars surrounded with a cover shell of Glass or Carbone fiber polymer (hybrid-steel). An experimental research program including 17 column specimens was prepared. The specimens were tested under an axial compression load till failure. The parameters studied were the Type of polymer, the percentage of steel in the hybrid reinforcement, the volume of internal stirrups, the rectangularity of the cross-section columns, and the percentage of fiber in the hybrid bars. Based on the obtained results, mathematical models were proposed and evaluated to predict the ultimate axial compressive strength. Generally, the results show that hybrid reinforced concrete columns exhibit acceptable levels of reliability index.

Keywords: hybrid CFRP-steel, hybrid GFRP-steel, Columns, Compression**.**

1. Introduction:

The corrosion of steel reinforcement in the reinforced concrete (RC) structures causes costly maintenance costs and decreases the functioning of structural components. Fiber-reinforced polymer composites are the sound and viable alternatives for steel reinforcement. Although FRP bars areconsidered high strength, lightweight, and good durability to replace the steel bars, yet their application is still limited, especially in compression concrete structures. The reason lies in FRP reinforced concrete (FRP-RC) structures is not has large deformation due to low elastic modulus and also exhibit linear elastic behavior. Also, the compression response of glass FRP (GFRP) bars is affected by the different modes of failure (transverse tensile failure, buckled GFRP bar, and shear failure). Therefore, appropriate design guidelines for using GFRP bars in Compression members must be established for general acceptance by practitioners due to the lack of experimental data. The (ACI, 2015)design guidelines still don't recommend using GFRP bars as longitudinal reinforcement in compression members. ACI 440.1R-15 highlights that further research is need for columns (ACI, 2015).

GFRP reinforcement as longitudinal reinforcement in columns or as compression reinforcement in flexural members shall have been not deemed to provide compressive resistance in design according to Canadian codes (CSA806-2006, 2006). The research on FRP-RC compression members begins with the study of the compression properties of FRP bars. Many experimental studies have shown that the ultimate compressive strength of FRP bars accounts for approximately 20%–70% of ultimate tensile strength. and the tensile elastic modulus is fundamentally the same as the compressive elastic modulus(Chaallal, O, Benmokrane, 1993);(Mallick, 1988). Longitudinal FRP bars have a significant influence on the axial compression performance of FRP-RC columns. The study shows that the axial load-carrying capacity of FRP-RC columns is 13%–16% lower than that of steel-RC columns for the same longitudinal reinforcement ratio. The load carried by the steel bars accounts for approximately 12%–16% of the total load carried by RC columns. Whereas glass-fiber-reinforced polymer (GFRP) bars account for about 3%–10% of the total load(Afifi, 2013).(Afifi, Mohammad Z.Mohamed, Hamdy M.Benmokrane, 2014).,(Alsayed SH, Al-Salloum YA, Almusallam T H & MA, 1999); (Afifi, Mohammad Z.Mohamed, Hamdy M.Benmokrane, 2014); (Pantelides CP, Gibbons ME, 2013); (Tobbi, H., Farghaly A. S., 2012; Tobbi, H.; Farghaly, A.S.; Benmokrane, 2014),. On account of the relatively low elastic modulus of GFRP bars, GFRP bars are more susceptible to buckling failure than steel bars (Alsayed SH, Al-Salloum YA, Almusallam T H & MA, 1999). Moreover, GFRP bars as stirrups tend to have lower confinement to concrete than steel bars with the same volumetric ratio (Brown J, 2012); (De Luca et al., 2010). Therefore, the design of the GFRP stirrup is indispensable and significant for GFRP-RC columns.

In general, reducing the stirrup spacing or increasing the volumetric ratio can strengthen the confinement to the longitudinal bars and core concrete, increasing the ductility for both steel- and GFRP-RC columns (Afifi, Mohammad Z.Mohamed, Hamdy M.Benmokrane, 2014); (Cusson D & Paultre, 1994), (Tobbi, H.; Farghaly, A.S.; Benmokrane, 2014). Changing the configurations of the stirrup to further improved the confinement is a further alternative. For GFRP-RC columns with a circular section, continuous circular spirals are frequently employed instead of hoops to increase the confinement of the stirrup. (Mohamed HM, 2014)compared and analyzed the effects of Hoops and spirals on the axial compression performance of GFRP-RC columns with a circular section. It found that Spirals can provide augmented confinement, leading to an increase in the ductility and load-carrying capacity of GFRPRC columns. In terms of a square-sectioned GFRP-RC column, to enhance the confinement on concrete, the volumetric ratio of an RC column can be increased by adding more tensile rebars in the stirrup (Tobbi, H., Farghaly A. S., 2012; Tobbi, H.; Farghaly, A.S.; Benmokrane, 2014) or encasing the sections in concrete (Hadi, M.N.S., Youssef, 2016). Compare to Hoops and spirals can further improve confinement to longitudinal reinforcement and core concrete, leading to an increase in Ductility and advanced seismic performance. (Jianwei et al., 2019)investigated the effects of the longitudinal reinforcement ratio, stirrup configuration (Spirals versus Hoops), and spacing on the load-carrying capacity longitudinal GFRP bars accounted for 3%-7% of the ultimate load-carrying capacity of the columns.

(Farghal & Diab, 2013) studied 18 circular short column specimens that were tested under an axial compression load, to investigate the gain strength of reinforced concrete (RC) columns confined with CFRP sheets The parameters studied were both the volume and configurations of CFRP sheets, the size of cross-section, the percentage of main reinforcement, and the volume of internal stirrups. On the basis of the obtained results, mathematical models (Egyptian code and American Concrete Institute code) proposed to predict the axial compressive strength of non-slender RC column strengthened by means of CFRP sheets are evaluated. Therefore, modifications in the studied models were considered. The modifications take the effective lateral confining pressure due to the presence of internal steel stirrups into account. The modified codes showed an acceptable approach to theexperimental results.(Raza et al., 2020)studied the behavior of Structural performance of FRP-RC compression members wrapped with FRP composites. Their study aims to propose new models for predicting the axial loading capacity of FRP reinforced CFFT columns. In the same year, also (Raza & Khan, 2020) studied the structural behavior of steel and GFRP-reinforced concrete columns having hybrid fibers (SHFC and GHFC columns).

As mentioned earlier, design codes do not provide provisions regarding FRP reinforced columns neither reliability-based calibration. Accordingly, this study presents a general design procedure for rectangular (hybrid-steel) reinforced columns under concentrically. The design procedure and reliability analysis are based on experimental data of 17 columns under concentric loading.

2. Research significance.

Currently, design codes do not provide design provisions for FRP reinforced concrete columns and require ignoring the compressive contribution of FRP bars. This study will assess researchers in updating ACI-440(ACI, 2015)and EC (ECP203) design provisions by presenting design guidelines supported basedreliability analysis to evaluate the safety level. The result shows that including the compressive contribution of (hybrid-steel) bars will result in more accurate results with an acceptable safety level.

3. Database and experimental results:

3.1Layout of experiments and test procedure

An experimental program of 17 RC columns carried out by the author.Theproperties of the used materials of the tested columns have been shown in Tables (1) to (4) and Fig (1). All columns were tested, at a concrete age of 28days. Three electrical strain gauges were attached to the surface of the column, stirrups and longitudinal bars to measure the strain induced in that column Fig (2), three dial gauges were also attached at mid-height and end of the specimens to measure the vertical and horizontal deformation of the specimens, as shown in Fig (2).

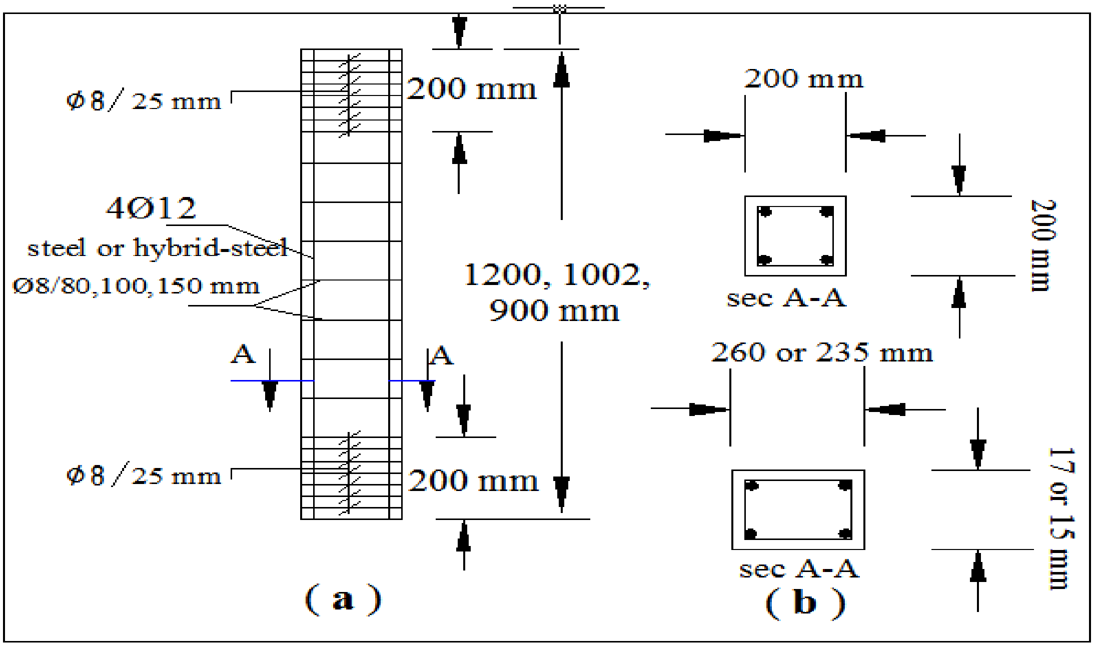

Fig. 1: Typical details of the tested columns

Table 1: Properties of the steel reinforcement.

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Table 2: Properties of the hybrid reinforcement.

Hybrid Bar size (mm)	Actual diameter (mm)	Type of hybrid	Yield Stress (MPa)	Ultimate stress (MPa)	Tensile modulus of elasticity (GPa.)	Elongation %
6/12	11.8	Steel – glass	360	522.5	165.0	3.5
8/12	11.8	Steel – glass	385	701.0	210.0	3.5
10/12	11.8	Steel – glass	400	862.2	235.0	3.5
6/12	11.8	Steel – carbone	385	522.5	214.0	3.19
8/12	11.8	Steel – carbone	405	701.0	232.0	3.19
10/12	11.8	Steel – carbone	445	862.2	255.0	3.19

Table 3: Poperties of the FRPbars.

Bar size (mm)	Actual diameter (mm)	Yield Stress (MPa)	Ultimate stress (MPa)	Modulus of elasticity (GPa)	Elongation %
8	8	240	320	200	18
12	11.5	605	770	200	20

Fiber Bar size (mm)	Actual diameter (mm)	Type of fiber bars	Tensile strength (MPa.)	Tensile modulus of elasticity (GPa.)	Ultimate strain%
12	11.8	glass	315	60	3.55
12	11.8	Carbone	345	155	3.19

Table 4: Details of the tested columns:

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Group No	Column No.	Cross section	Longitudinal Reinforcement		Transverse Reinforcement		Concrete compressive strength f_{cu} N/mm2
			steel	hybrid	steel	hybrid	
A	C1	200×200	4Φ12	-	Ø8/120mm	-	24.5
	C2	200×200	-	4Φ10/12	Ø8/120mm	-	24.5
	C3	200×200	-	4Φ8/12	Ø8/120mm	-	24.5
	C4	200×200	-	4Φ6/12	Ø8/120mm	-	24.5
	C5	200×200	4Φ12 GFRP-bar		Ø8/120mm	-	24.5
B	C6	200×200	-	4Φ10/12	Ø8/120mm	-	35.6
	C7	200×200	-	4Φ10/12	Ø8/120mm	-	44.9
C	C8	200×200	-	4Φ10/12	Ø8/80mm	-	24.5
	C9	200×200	-	4Φ10/12	Ø8/150mm	-	24.5
D	C10	200×200	-	4Φ10/12&% of fiber=85% C2	Ø8/120mm	-	24.5
	C11	200×200	-	4Φ10/12&% of fiber=75% C2	Ø8/120mm	-	24.5
E	C12	235×170	-	4Φ10/12	Ø8/120mm	-	24.5
	C13	260×150	-	4Φ10/12	Ø8/120mm	-	24.5
F	C14	200×200	4Φ12CFRP-bar		-	Ø8/120mm	24.5
	C15	200×200	-	4Φ10/12	-	Ø8/120mm	24.5
	C16	200×200	-	4Φ8/12	-	Ø8/120mm	24.5
	C17	200×200	-	4Φ6/12	-	Ø8/120mm	24.5

For group A, ColumnC1 was reinforced with longitudinal steel reinforcement asa reference column, while the remainders of the columns were reinforced with hybrid bars as shown in table (4). It is worth mentioning end zones, of all studied columns were provided with closed stirrups spaced 25mm along a distance 200mm.

Columns C2, C3, and C4 were reinforced with four (hybrid GFRP-steel)bars 12 mm total diameter as longitudinal reinforcement.In the form of inner steel bars core Ø6, Ø8, Ø10mm respectively, surrounded with a shell cover of glass fiber polymer. The transverse reinforcement was steel bars with 8 mm diameter;see Fig. (1) and Tab. (4).

Column C5 was reinforcement with four-bar 12 mm from glass fiber. For comparison,group B, Columns C6 and C7 were the same as columns C2 but the concrete compressive strengthen was 35.6 and 44.9 Mpa respectively. Also for group C,columns C8, and C9, were the same as column C2but the spacing between stirrups were 80 and 150 mm respectively. However,group D, columns C10 and C11 were reinforced as the same as column C2but the volumetric ratio in the GFRP used part was 85 and 75% corresponding, to that of column C2 respectively.

Group E, ColumnsC12 and C13 the section was 260×150 and 235×170mm respectively and reinforced with four bars of 12mm from hybrid GFRP-steel.

For group F, Column C14 reinforcement with four-bar 12 mm fromcarbon fiber. The remainder of columns C15, C16, and C17 was reinforced with four bars 12 mm totaldiameter as longitudinal reinforcement in the form of inner steel bars core Ø6, Ø8, Ø10mm respectively,surrounded with a cover of Carbone fiber polymer (hybrid CFRP-steel). All columns were tested in their original condition to serve as a control Column,see Fig.2.

The failure compressive load resulted from the experimental test were studied and analyzed elsewhere (Mostafa Ahmed Mohamed, Abdorced El-Rahman Megahid Ahmed, n.d.) included in Tab. (6).

Fig. 2: Testing of column specimens

4. Nominal axial capacity

The nominal axial capacity of concentrically loaded short columns reinforced with longitudinal steel bars can be computed by summing the contribution of the concrete and steel in compression. At the ultimate limit state, the steel bars yield (i.e. $\varepsilon_{steel} \geq 0.002$) and the column capacity can be computed as given in Eq. (1) or Eq. (2). According to either ACI orCanadian codes respectively. The ACI-440[1] and CAN/CSA S806 [3] state that the contribution of FRP reinforcement should be neglected in compression. Based on this recommendation, the nominal axial capacity of FRP-RC columns can be computed as given in Eq. (2).

$P_n = 0.85f'_c\,(Ag - A_s) + A_sf_y$ Eq. (1).

$P_n = 0.85f'_c\,(Ag - Af\,)$ Eq. (2).

Where P_n is the nominal axial capacity, Ag is the columns' gross area; A_f is the area of FRP bars. In the surveyed literature, several researchers suggested including the FRP effect in nominal axial capacity through different approaches, however no available researches for approaches for columns reinforced with hybrid bars were found.

One approach is to obtain the stress in the FRP bars by assuming a linear stress-strain relationship (*i.e.* $\sigma_{FRP}= E_f \times \varepsilon$),$E_f$ is the elastic modulus of FRP bars and limiting the strain$\varepsilon$to 0.002 (Eq. (3)).

$P_n = 0.85f'_c(A_g - A_f) + 0.002E_f A_f$ Eq.(3).

In this study, the maximum nominal compressive strength (P_n) of hybrid RC columns' specimens assumed to be predicted according to the modificated models (ACI, ECs, Afifi, Tobbi and Mohamed, H.MAfifi.) as listed in table 6. Thenominal axial loads *Pn* is predicted according to these modified models and were listed in Tab. 7.

Table 5: Various axial capacity models for evaluation

Capacity mode	The relationship for capacity model	Model modifications
ACI-318–08	P_n = 0.85f'c(A_g - Af)+fyAs	P_n = 0.85f'c(A_g - Ah)+fhAh
ECs	P_n = 0.9[0.8X0.85fcc(A_g - Af)+fyAf	P_n = 0.9[0.8X0.85fcc(A_g - Ah)+fhAh
Afifi et al.	P_n = 0.85fc(A_g - Af)+.002EfAf	P_n = 0.85f'c(A_g - Ah)+.002EhAh
Mohamed et al.	P_n = 0.85fc(A_g - Af)+0.35ffAf	P_n = 0.85f'c(A_g - Ah)+0.35f_hAh
Tobbi et al.	P_n = 0.85fc(A_g - Af)+.003EfAf	P_n = 0.85f'c(A_g - Ah)+.003EhAh
Current study	P_n = 0.85f'c(A_g - Ah)+0.30$f_h A_h$	

(Hybrid –Steel)=FRP and Steel

Where P_n is the nominal axial capacity, A_g is the columns' gross area; A_h , f_h and E_h are thetotal area, yield stress andthe elastic modulus of thelongitudinal reinforcement (hybrid –steel)respectively, and$f_c$is the concrete strength

4.1 Axial Strength Model

The maximum compressive strength (P_n) of hybrid reinforced concrete columns was calculated according to the selected modificated models (ACI, ECs, Afifi, Tobbi, Mohamed, H.MAfifi and current study) and listed in table 5. The calculated values of P_n are compared with those obtained experimental data available in the literature review, see table 6. In the light of the average value, stander deviation, and correlation factor for each of the estimated values in Table 6, it would be decided that. The applied models better accurately predict the nominal axial load of reinforced concrete (RC) columns using (hybrid-steel). Such a prediction is better from the author's point of view the fact that the proposed models applied in this study take into consideration the effect of the new(hybrid-steel) to that corresponding to the yield strain of the steel bars.

Table 6: Analytical verification of maximum loads for the tested columns:

Group No	Column No.	$P_{max.}$	Prediction results											
			Modified Egyptian code (EC)		Modified ACI cod		Modified Afifi et al.		Modified Mohamed, H.M Afifi et al.		Modified Tobbi et al.		Current study	
			P_n (KN)	R_{max} (%)	P_n (KN)	R_{max} (%)	P_n (KN)	R_{max} (%)	P_n (KN)	R_{max} (%)	P_n (KN)	R_{max} (%)	P_n (KN)	R_{max} (%)
A	C1	862	731.29	84.84	837.26	97.13	683.76	79.32	737.37	59.54	683.85	79.33	714.31	82.87
	C2	930	755.70	81.26	864.38	92.94	683.79	73.53	746.86	59.36	823.91	88.59	719.74	77.39
	C3	881	749.60	85.09	857.60	97.34	683.77	77.61	744.48	60.11	823.87	93.52	718.38	81.54
	C4	852	739.43	86.79	846.30	99.33	683.74	80.25	740.53	60.03	823.84	96.69	716.12	84.05
	C5	833	721.12	86.57	825.96	99.15	683.63	82.07	733.41	69.83	823.67	98.88	712.05	85.48
B	C6	1210	1024.36	84.66	1174.08	97.03	993.49	82.11	1056.56	73.39	1197.04	98.93	1029.44	85.08
	C7	1345	1249.45	92.90	1433.56	106.58	1252.97	93.16	1316.04	78.35	1509.67	112.24	1288.92	95.83
C	C8	915	755.70	82.59	864.38	94.47	683.79	74.73	746.86	58.73	823.91	90.04	719.74	78.66
	C9	853	755.70	88.59	864.38	101.33	683.79	80.16	746.86	59.46	823.91	96.59	719.74	84.38
D	C10	880	745.53	84.72	853.08	96.94	683.78	77.70	742.90	59.62	823.89	93.62	717.48	81.53
	C11	865	727.23	84.07	832.74	96.27	683.77	79.05	735.78	59.61	823.87	95.24	713.41	82.48
E	C12	890	755.70	84.91	847.09	95.18	666.50	74.89	729.57	61.44	803.08	90.23	702.45	78.93
	C13	875	755.70	86.37	863.51	98.69	682.93	78.05	745.99	63.43	822.86	94.04	718.87	82.16
F	C14	781	733.33	93.90	839.52	107.49	683.72	87.54	738.16	65.68	823.80	105.48	714.77	91.52
	C15	949	774.01	81.56	884.72	93.23	683.81	72.06	753.98	58.57	823.93	86.82	723.81	76.27
	C16	897	757.74	84.47	866.64	96.62	683.79	76.23	747.65	60.07	823.90	91.85	720.19	80.29
	C17	837	749.60	89.56	857.60	102.46	481.99	81.69	744.48	60.37	823.88	98.43	718.38	85.83
Average (%)			86.05		98.36		79.42		86.04		94.74		83.19	
Stander deviation			3.51		4.13		5.16		4.71		7.15		4.89	
Correlation factor R^2			0.97		0.97		0.95		0.96		0.94		0.96	

Rmax: the ratio of predicted maximum load to that obtained experimentally 'Pn/Pmax'

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4.2Validation of the models proposals

In light of the aforementioned context, the load-carrying capacity of reinforced concrete (RC) columns using (hybrid-steel) predicted according to the modified models suggested in this study showed a better estimation approaching the experimental results,seeTab. 5 and Fig. 5.

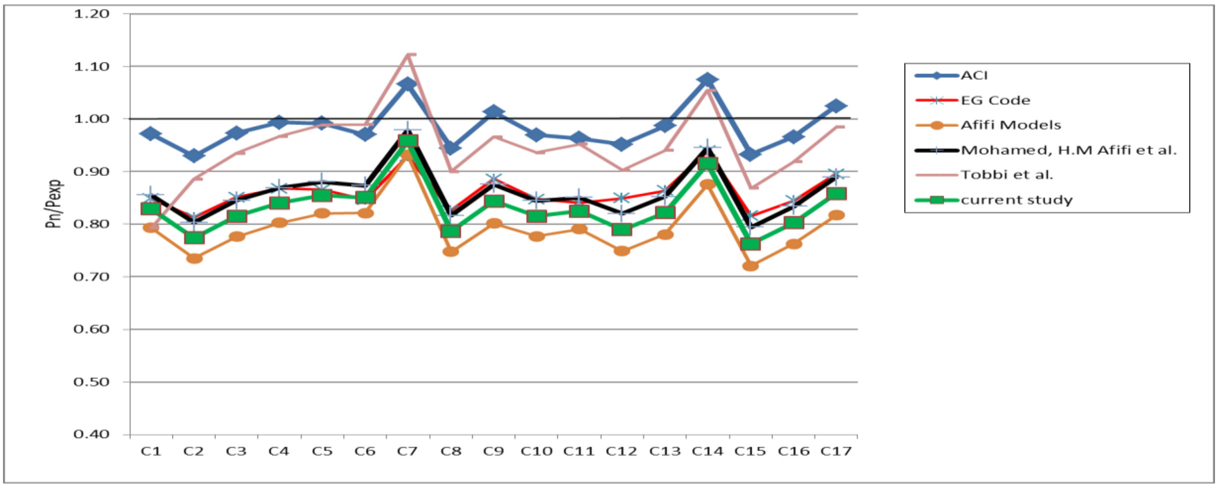

Figure: 5 Predicted-to-experimental ratio of maximum load (P_n/P_{max}) for the different columns

5. Conclusions:

In the light of experimental study concerning the strain and the available database on the behavior of new hybrid reinforced concrete columns reinforced with the longitudinal reinforcement in the form of inner steel bars core surrounded with a cover of fiber polymer (hybrid FRP-steel) under concentric loading as well as the performed analytical verifications, The following key conclusions can be drawn:

1. The proposed empirical model by modifying (ACI, EG, Mohamed, H.MAfifiand current study) for predicting axial load-carrying capacity of hybrid-reinforced columns portrayed a good performance over the developed database of 17 specimens with R^2 = 0.97, 0.97, 0.96 and 0.96 respectively. This performance substantiates its accuracy and applicability.
2. The reliability index was not sensitive to changes in Type of fiber, the shape of cross-section, the percentage of main reinforcement, and the volume of internal stirrups for the studies case. However, the reliability index exhibited some fluctuations with concrete strength.
3. Using a 0.30 reduction factor for model (current work.) to account for the reduction in the compressive strength of the (hybrid FRP-steel) bars as a function of their tensile strength provided accurate and conservative predictions of the nominal capacity of the tested (hybrid FRP-steel) RC columns. More experimental evidence and future studies are needed. However, to more accurately define the

compressive properties of (hybrid FRP-steel) bars and to investigate the effect of column size.

4. The comparison between the predictions of the proposed empirical model and maximum load for the axial load-carrying capacities of 17 hybrid-steel reinforced columns confirmed the accuracy of the proposed empirical model for the prediction of the axial load carrying capacity with averageparticularly R^2 = 0.96. Thus, the proposed models are accurate enough to be used for the analysis and design of hybrid-steel reinforced columns.

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Non

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