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Models for Predicting Strength of Biaxially Loaded RC Columns Strengthened using NSM-CFRP Strips and Fabric

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Abstract

An experimental study on large scale short reinforced concrete (RC) columns strengthened using near surface mounted (NSM) carbon fiber reinforced polymer (CFRP) strips and confined with CFRP fabric was carried out to determine the effects of the strengthening mechanism on the load carrying capacity of RC columns. The specimens were subjected to concentric and eccentric loading conditions resulting in axial and biaxial bending. The specimens were categorized according to the applied eccentricity ratio. Based on part of the experimental results, multiple empirical Linear and Nonlinear models were developed to predict the load carrying capacity for concentrically and biaxially loaded columns strengthened with NSM CFRP strips and confined with CFRP fabric wraps using the resultant eccentricity ratio as a parameter. The results obtained from the empirical models are validated against the experimental results. The empirical models were able to predict the load carrying capacity for axially and biaxially loaded columns with an average Mean Absolute Percent Error (MAPE) of 7.1% for the Nonlinear models and 24.0% for the Linear models. It has been concluded that the developed Nonlinear models can be used as practical tools for accurately predicting the capacity of RC columns strengthened with NSM-CFRP strips and CFRP wraps subjected to axial loading and biaxial bending conditions.

Keywords: RC columns, carbon fiber reinforced polymer wrap, near surface mounted carbon fiber reinforced polymer, column capacity, prediction, biaxial.

1 Introduction

The deterioration of RC members' properties triggered researchers to develop strengthening materials and investigate their effects and behaviour to overcome this issue. One of these materials is CFRP which has been extensively investigated and used as strengthening material for RC members such as beams and columns [1-4]. CFRP material comes in various shapes and configurations. It comes as plates, strips and fabric. The CFRP plates were used for flexural and shear strengthening of RC beams and columns [5-9]. CFRP strips were used in NSM technique for flexural strengthening of RC columns. The NSM-CFRP strengthening technique requires minimal surface preparation in comparison to externally bonded plates which increases the flexural capacity of the structural element significantly [5,6,10-14]. CFRP fabrics were used for anchoring CFRP plates as well as for coffining RC columns to enhance their axial capacity and ductility [14-18].

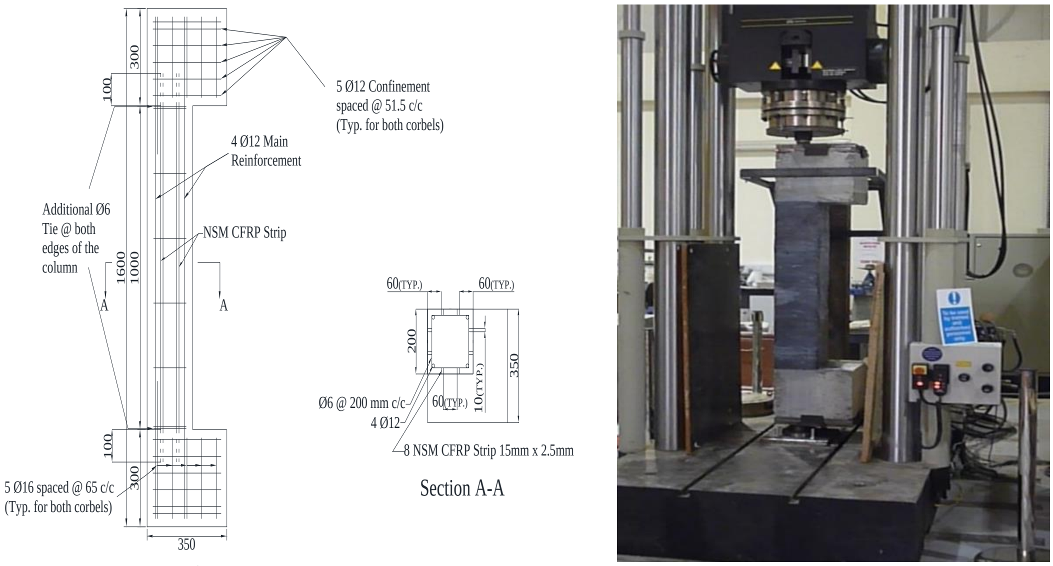
The reliability and efficiency of NSM-CFRP strips combined with CFRP confinement were investigated by Abokwiek et al. [14]. They carried out an extensive experimental study to improve the concentric and eccentric loading capability and ductility of RC columns. In the analysis of specimens' capacity, the impact of various eccentricity ratio combinations along with multiple NSM-CFRP mechanisms and CFRP confinement were considered in two directions simulating biaxial bending effects. The improvement in the load carrying capacity of the proposed strengthening mechanism for confined columns strengthened with NSM-CFRP strips in axial and biaxial bending ranged from 36 to 49% and 76 to 128%, respectively.

Based on the obtained experimental results, multiple linear and nonlinear empirical models are developed and presented in this paper. The models were developed to predict the load carrying capacity for concentrically and biaxially loaded columns covering both the unstrengthened and strengthened columns with NSM-CFRP strips and fabric wraps using the eccentricity ratio resultant as a parameter. The predicted load carrying capacity values were validated against the experimental results and showed a nearly perfect fit for the Nonlinear models. As a result, the developed Nonlinear empirical models can be used as a useful tool for predicting the load carrying capacities of RC columns strengthened with NSM-CFRP strips and CFRP fabric wraps and subjected to axial loading and biaxial bending conditions at various eccentricities.

2 Materials and Specimens Details

Several specimens with the same RC column arrangement were cast and tested. The number of CFRP confinement layers along with the applied eccentricity were varied. The specimens were 1000 mm long with a square cross-section of 200 x 200 mm. They were made from ready mixed concrete of 22 MPa compressive strength at 28 days. Reinforcement consisted of 4Ø12 longitudinal bars providing a reinforcement ratio (ρ) of 1.13%. Six stirrup ties of Ø6@200 mm c/c were distributed along the height of the column with additional ties at the end of the specimen to prevent premature failure between the specimen and the corbel. The steel had an average yield strength and modulus of elasticity of 590 MPa and 200 GPa, respectively. In order to simulate biaxial bending effect and reach the desired eccentricity ratio, two corbels were added at each end of the column, positioned at one corner and they were casted monolithically with the specimen. The corbels were 300 mm deep each with a square cross-section of 350 x 350 mm. Some of the specimens were strengthened using different number of CFRP wraps and strips. The strengthening material of CFRP wrap and strips were supplied and applied to the specimens using their compatible epoxies for each according to their manufacturer recommendation. The CFRP plate is 1.5 mm thick, with modulus of elasticity of 165 MPa, ultimate tensile strength of 3100 MPa and strain at rupture of 1.7%. While the CFRP wrap is 0.17 mm thick, with modulus of elasticity of 230 MPa, ultimate tensile strength of 3900 MPa and strain at rupture of 1.5% [19,20]. The two types of epoxies used have modulus of elasticity in the range of 10 to 4.5 MPa and have ultimate tensile strength in the range of 25 to 30 MPa [21,22].

The specimens were divided into groups according to the applied eccentricity ratio. The eccentricity ratio was varied in both directions X and Y ranging from (0-0.75) with an increment of 0.25 with different eccentricity ratio combination. One control specimen in each group was not strengthened with CFRP strips or wraps and was designated as 0S0W. The specimens in each group were strengthened using different CFRP strips and varied number of CFRP wrap layers. The specimens of the subgroup used in this study have eight strips and two wraps and designated as 8S2W. Figure 1. shows the details of a typical specimen and the test setup.



(a) Reinforcement and strengthening details

(b) Test mounted specimen

Fig 1. Specimen details and test setup

3 Experimental Program and Results

A summary of part of the experimental results comprising of ultimate attained load (P_u) for each tested specimen with different eccentricity ratio is shown in Table 1.

Table 1. Experimentally measured axial load carrying capacity

Group Sr. No.	Eccentricity Ratio	Eccentricity Ratio	Specimen Designation	P_u (kN)
1	($e_x/b_x= e_y/b_y= 0.0$)	0	1-0S0W	1117
			1-8S2W	1520
2	($e_x/b_x=e_y/b_y= 0.25$)	0.35	2-0S0W	391
			2-8S2W	689
3	($e_x/b_x=0.25$, $e_y/b_y= 0.50$)	0.56	3-0S0W	252
			3-8S2W	509
4	($e_x/b_x=e_y/b_y= 0.50$)	0.71	4-0S0W	175
			4-8S2W	400
5	($e_x/b_x= 0.50$, $e_y/b_y= 0.75$)	0.90	5-0S0W	137
			5-8S2W	292

The control specimens in each group were used as benchmark to measure the performance of the other strengthened specimens within or outside the group. It was observed that confinement with CFRP wrap increases the load carrying capacity of the specimens at all eccentricity ratios. However, the increase in capacity depends on the eccentricity ratio. In addition, the use of NSM-CFRP strips has contributed to the flexural strength of the specimens along with the CFRP wraps. It was observed that the increase in flexural capacity was lower at higher eccentricity ratios. Moreover, the increase in the number of CFRP wrap layers has lower influence on the flexural capacity in comparison to the axial capacity.

4 Empirical Prediction Models and Results

4.1 Nonlinear Empirical Models for Capacity Ratio

Two Nonlinear empirical models were developed for both unstrengthened and NSM-CFRP strengthened specimens, as illustrated in Fig. 2. The plot shows the capacity ratio (PR = PCap/PAxial) versus the eccentricity ratio (ER), representing the experimental to predicted axial load. The empirical models were designed for one non-strengthened specimen (0S0W) and one group of strengthened specimens (8S2W). Figure 2 also shows the exponential reduction in the capacity ratio (PR) of the cross-section under bidirectional bending conditions, along with the corresponding R^2 values. The eccentricity ratio (ER) used in developing the models is based on the resultant eccentricity ratio calculated from the eccentricity ratio employed in this study.

The resultant eccentricity ratio, as presented in Table 2, shows that as the eccentricity ratio (ER) increases, the capacity ratio (PR) decreases exponentially. Figure 2 also indicates that the curves for non-strengthened specimens decline more rapidly than the curves for strengthened specimens at low eccentricity ratios. However, at higher eccentricity ratios, the reduction rate in capacity ratio becomes almost the same for both cases. Table 2 provides a summary of the statistical performance, including R^2, MAPE, RMSE, and NMSE, of the developed empirical Nonlinear models. Notably, the regression analysis results demonstrate that the R^2 values for all specimens are very close to one, indicating that the capacity ratio (PR) of columns under biaxial bending, with and without NSM-CFRP strips and wraps, can be reasonably predicted using these developed models.

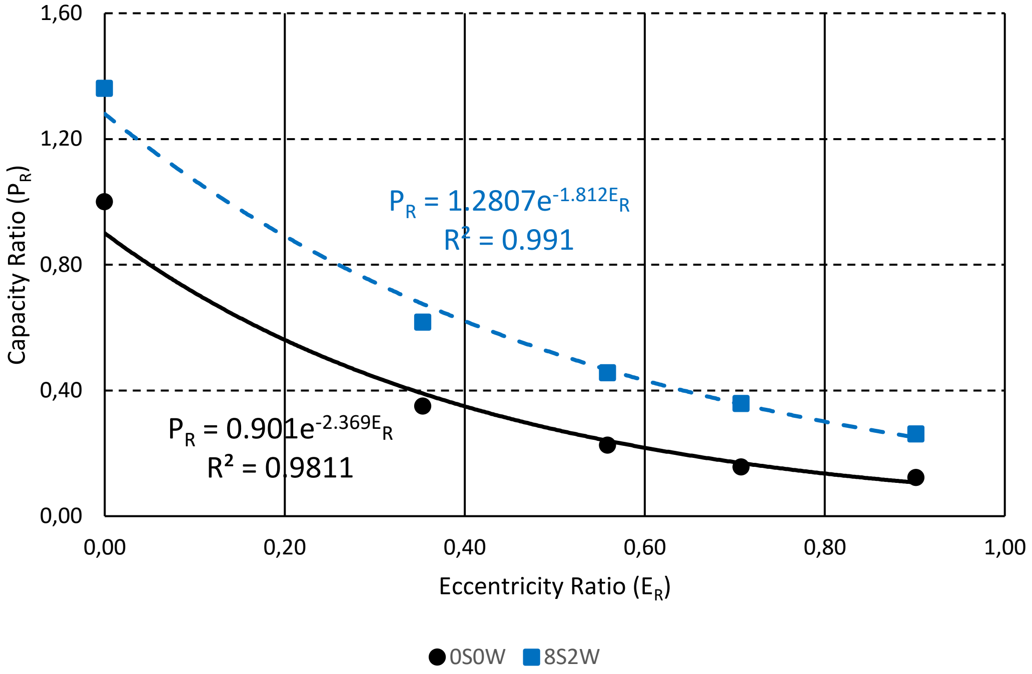


Fig 2. Effect of eccentricity ratio in biaxial capacity of columns

Table 2. Nonlinear empirical models of capacity ratio (P_R) and eccentricity ratio (E_R)

Specimen	Empirical Model	R^2	MAPE	RMSE	NMSE
0S0W (no Strip, no Wrap)	$P_R = 0.901e^{-2.369E_R}$	0.981	9.1%	0.049	0.023
8S2W (8 Strips, 2 Wraps)	$P_R = 1.2807e^{-1.812E_R}$	0.991	5.0%	0.045	0.013

4.2 Linear Empirical Models for Capacity Ratio

In similar fashion to the Nonlinear empirical models, two Linear empirical models for unstrengthened and NSM-CFRP strengthened specimens were developed as shown in Fig. 3, where the experimental to predicted axial load, i.e., capacity ratio (P_R = PCap/PAxial) versus the eccentricity ratio (E_R) is presented. Empirical models were developed for two types of specimens: one non-strengthened specimen (0S0W) and one strengthened specimen (8S2W), as depicted in Fig. 3. The plot shows the exponential reduction in the capacity ratio (P_R) of the cross-section under bidirectional bending conditions, along with the corresponding R^2 values. As the eccentricity ratio (E_R) increases, the capacity ratio (P_R) decreases. Additionally, it is evident from Fig. 3 that the curve for the strengthened specimens decreases more rapidly compared to the curve for the unstrengthened specimen. At higher eccentricities, the models deviate from the experimental values, leading to negative results in capacity. Table 3 provides a summary of the statistical performance, including R2, MAPE, RMSE, and NMSE, of the developed empirical models. Notably, the R^2 values for all specimens range from 0.86 to 0.90, indicating that the capacity ratio (P_R) of columns under biaxial bending, both with and without NSM-CFRP strips and wraps, can be reasonably predicted using these developed models at lower eccentricity ratios.

Table 3. Linear empirical models of capacity ratio (P_R) and eccentricity ratio (E_R)

Specimen	Empirical Model	R^2	MAPE	RMSE	NMSE
0S0W (no Strip, no Wrap)	$P_R = -0.969E_R + 0.8597$	0.857	26.6%	0.1225	0.1430
8S2W (8 Strips, 2 Wraps)	$P_R = -1.206E_R + 1.2188$	0.902	22.0%	0.1231	0.0981

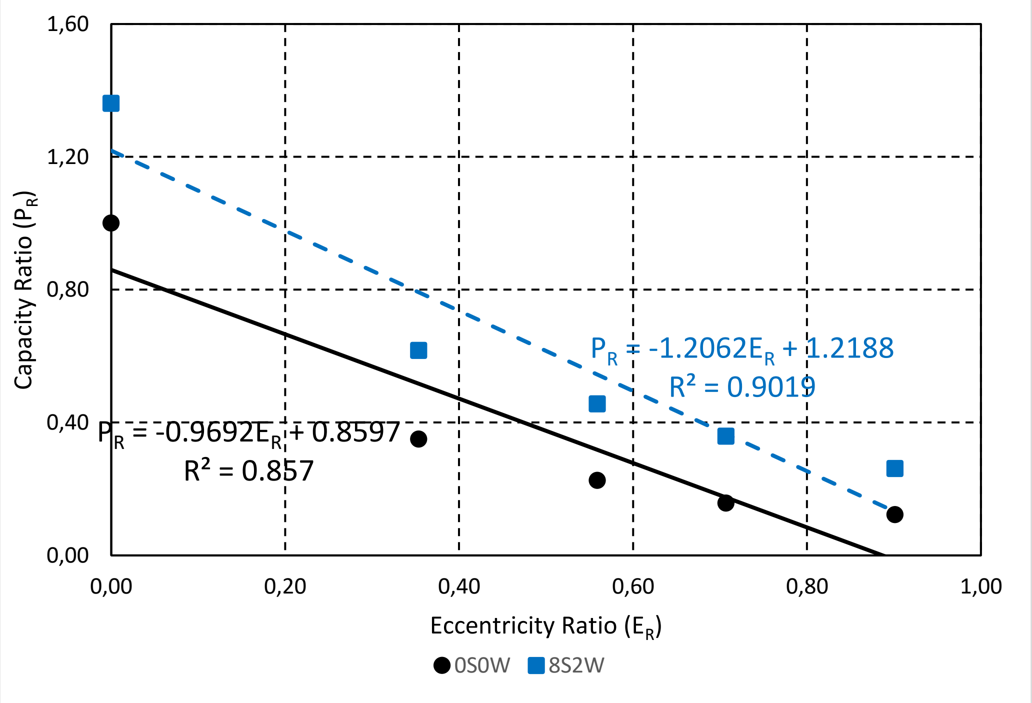


Fig. 3 Effect of eccentricity ratio in biaxial capacity of columns

5 Results and Discussions

Table. 4. shows the results of experimental and empirical prediction of ultimate load (P_u) for both Nonlinear and Linear models for the tested columns. The experimentally measured ultimate load values and the empirically predicted ones are in good agreement, especially for the Nonlinear prediction models. The average MAPE of the Nonlinear model predictions is 7.1% while that for the Linear model is 24.04%. The nonlinear models have near perfect fit with R^2 equal to 0.99 for the strengthened specimens and 0.98 for the unstrengthened specimens. The Linear empirical models were less accurate with R^2 ranging between 0.86 and 0.90

For the concentrically loaded specimens, where eccentricity ratio is zero in both directions (i.e., $e_x = e_y = 0.0$), the Nonlinear models, were able to predict the load carrying capacity for the unstrengthened and strengthened specimens with MAPE values of 9.9% and 5.9%, respectively. However, the Linear models predictions were less accurate with MAPE values of 14.0% and 10.4%. Such close agreement suggests the adequacy of the developed Nonlinear empirical models for predicting the axial load carrying capacity for RC columns subjected to concentric loading favouring the aforementioned empirical models. Similarly, for the specimens subjected to loads with equal and different eccentricity ratio in both directions, the Nonlinear models predictions have a MAPE ranging from 1.9 to 12.9% while the Linear models predictions have MAPE ranging from 2.2 to 49.0% as shown in Table 4.

It is clear from the comparison of values of the load capacities predicted by the prediction models and that of the experimental results, the Nonlinear models are able to accurately predict the load capacities of eccentrically loaded columns under biaxial loading. These models may be used in lieu of exhaustive experimental programs to predict the capacity of unstrengthened columns and for columns strengthened using NSM-CFRP strips with CFRP fabric wraps under axial and biaxial loading.

Table 4. Comparison between experimental and empirical predictions

Specimen Name	Resultant Eccentricity Ratio	P_u Exp (kN)	P_u Emp,NL (kN)	P_u Emp,L (kN)	MAPE	
					Emp,NL (%)	Emp,L (%)
1-0S0W	0	1117	1006	960	9.9	14.0
1-8S2W	0	1520	1431	1361	5.9	10.4
2-0S0W	0.35	391	439	581	12.3	48.7
2-8S2W	0.35	689	759	890	10.1	29.1
3-0S0W	0.56	252	267	354	6.0	40.5
3-8S2W	0.56	509	519	607	1.9	19.2
4-0S0W	0.71	175	183	181	4.5	3.3
4-8S2W	0.71	400	388	391	3.0	2.2
5-0S0W	0.90	137	119	-	12.9	-
5-8S2W	0.90	292	280	149	4.1	49.0
Average					**7.1**	**24.0**

6 Conclusions

- Nonlinear and Linear empirical models for predicting ultimate load capacity of unstrengthened and strengthened columns under axial and biaxial loading applied at different eccentricity ratios were developed.
- The Nonlinear empirical models were able to predict the ultimate load of the axially and biaxially loaded columns with high accuracy compared to experimental results with an average MAPE of %7.1.
- The developed Nonlinear empirical models with respect to the eccentricity effects have exponential decay and a near-perfect fit to the experimental results, with R^2 in the range of 0.98-99%.
- Due to their high accuracy, the Nonlinear models can be used in state of expensive experimental programs to predict the capacity of columns strengthened with NSM-CFRP strips with CFRP fabric wraps under axial and biaxial loading.
- The Linear empirical models, although they are simple and easy to use, however they were less accurate with MAPE ranging between 22.0% and 26.6%, and R^2 ranging between 0.86 and 0.90.

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