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Numerical Investigation for the Structural Behaviour for Partially-Loaded High Strength Concrete Columns Under Uniaxial Loading

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Abstract*:*

This research aims to study and validate a numerical model for the structural behavior of partially loaded square high strength reinforced concrete (HSC) columns with an eccentricity of 50 mm from the center (e/h = 0.5) using ABAQUS. For this purpose, nine short HSC columns were used after they strengthened with carbon fiber reinforced polymer (CFRP) sheets in various schemes and tested experimentally in terms of their ultimate strengths and complete response to the load-vertical deflections obtained from a previous research paper under publication to be used to check the integrity of the arithmetic results. Further parameters were then investigated using the verified model, such as the influence of extra CFRP layers, different load eccentricities (e/h), and initial loading ratios. Through rapprochement in the values of both the ultimate load and deflections, the numerical analysis demonstrated a high level of accordance with the experimental findings. Results also showed that increasing the number of CFRP sheets for specimens strengthened comprehensively with CFRP laminates in both transverse and longitudinal directions increased significantly the ultimate load capacity. At the same time, by decreasing the eccentricity ratio (e/h), the maximum strength and deflections for all specimens strengthened fully or partially with CFRP sheets were enhanced. Indeed, the results showed that increasing the initial loading ratios of the strengthened samples led to a decrease in the ultimate load.

Keywords**:** HSC, ABAQUS, eccentricity load, CFRP laminates, numerical study.

1. Introduction

Broadly, a column is an essential structural part of a building as it carries loads from slabs and beams to the bases. Columns in buildings may be vulnerable to catastrophes such as storms or earthquakes, or they may be built using outdated specifications [1]. As a result of these factors and many others, columns may be unable to withstand the imposed loads. Consequently, these columns should be strengthened by utilizing several ways such as CFRP laminate wrapping, jacketing technique, near-surface mounted (NSM), or a combination of all these techniques [2]. A great deal of experimental studies on typical damaged and undamaged concrete columns showed the positive effect of the above strengthening techniques [3], [4], [5]. In addition, other novel parameters that could not be researched experimentally could be carried out using numerical investigations. Chellapandian et al. [6] concluded from their study that the experimental and numerical results were quite close when testing square reinforced concrete columns strengthened with CFRP laminates by used ABAQUS to evaluate the effect of strengthening on the initial stiffness and change in failure modes of reinforcement concrete column. The study results also indicated to a slight difference (less than 5%) between the experimental and numerical results. The authors used the verified finite element analysis for other parametric cases such as CFRP ratio alteration. The effect of using CFRP strengthening on the stiffness, strength, and ultimate ductility of RC columns under compression has been proven to be effective. Noroozieh et al. [7] used the finite element modelling to perform a numerical analysis for the experimental results obtained from Sarfraz' work [8], which is represented by wrapping the reinforced columns with hybrid technology with the use of NSM rebars and fibre-reinforced polymer (FRP) jackets. Through the study, the results of the numerical were validated with the experimental data. In addition, the reasonable accuracy of the results provided a tool for the authors to carried out a comprehensive investigation for the effect of various parametric study such as axial load ratio, steel reinforcement diameter, number of CFRP layers, concrete compressive strength, and FRP confinement over the entire column height. The results showed that the required ductility can be achieved by selecting the appropriate number of CFRP layers for strengthening concrete. Hemzah et al. [9] used ABAQUS to perform a numerical study for the structural behavior of self-compacting concrete short columns strengthened using various approaches such as CFRP wrapping, NSM and combination approach (hybrid) under concentrated load. Through convergence in the values of the study results in terms of the ultimate load and maximum displacement, the numerical investigation found to have a high level of accordance with the experimental findings. In addition, the authors also conducted numerically various parametric studies represented by the effect of expanding the number of CFRP sheets, the difference in the compressive force of concrete, and the increasing the initial loading ratios of the strengthened specimens. The results showed that the most significant height in the maximum load of all specimens were in the hybrid strengthening technique with full CFRP and (NSM) when increasing the layers of CFRP sheets. Obaidat [10] used the ABAQUS tool to create a model based on finite elements for samples augmented with partially carbon fiber reinforced polymer sheets (CFRP) warping in comparison to other initially created samples. The author also investigated the impact of reducing the distance between CFRP sheets and modifying the number of CFRP layers. The experimental and numerical results were found to be very compatible. Besides that, the researchers concluded that expanding the layer thickness of CFRP strips and lowering the distance between CFRP laminates could increase the columns' ultimate load capacity.

In the light of the above concluded points, the purpose of this study is to create a numerical model based on laboratory results collected by the authors for nine short HSC partially damaged columns with a squared cross section under eccentric load. The first column was tested to failure and considered as a control column. In contrast, the remaining eight columns were divided into two groups in which the first one was tested after been loaded by an initial load ratio of 25% of the designed ultimate load and the second was loaded by a load ratio of 50% of the ultimate load to be strengthened with CFRP sheet technique. Also, the authors intend to investigate additional factors using the validated numerical model, like the effect of increasing CFRP strips, difference eccentric load(e/h), and the initial loading ratios.

2. Material

The numerical study consists of simulating the experimental work, which involves nine columns in which one was loaded to failure and considered a control column. The other eight columns were divided into two groups in which the first was tested after been loaded by an initial load ratio of 25% of the designed ultimate load, and the second was loaded by a load ratio of 50%, then strengthened with CFRP strengthening technique, as given in Table 1 [11]. The materials in the modelling of these columns included concrete, steel reinforcement (primary and transverse reinforcement), steel plates, CFRP sheets were as follows.

Table 1 Details of the specimens of the experimental work

Group number	Specimen load / Ultimate load ratio	Specimens designation	No strengthening
		CC	No strengthened
Group 1	(25%) *	CQFFL	Full longitudinal wrapping with CFRP for all column faces
		CQRF	Full longitudinal wrapping with CFRP for rear face only
		CQFFW	Full horizontal wrapping with CFRP for clear column height
		CQ25FW	Horizontal wrapping with CFRP for 250 mm length at column mid-height
Group 2	(50%)**	CHFFL	Full longitudinal wrapping with CFRP for all column faces
		CHRF	Full longitudinal wrapping with CFRP for rear face only
		CHFFW	Full horizontal wrapping with CFRP for clear column height
		CH25FW	Horizontal wrapping with CFRP for 250 mm length at column mid-height

* *The specimens were loaded with an initial load of 25% of the final design load. Then it was strengthened and reloaded until failure.*

** *The specimens were loaded with an initial load of 50% of the final design load. Then it was strengthened and reloaded until failure.*

2.1 High Strength Concrete (HSC)

All specimens were prepared with identical dimensions of a square cross-section (100 × 100) mm and a total length of 800 mm. The length between the corbels was 500 mm, and each corbel head has a height of 150 mm, as shown in Figure 1. In the 3D finite element analysis, concrete is treated as a solid element. **(**Table 2 shows the general properties used in modelling HSC).

Table 2 General properties used in modeling HSC

Dilation angle (Degree)	Eccentricity (mm)	Fb_0/fc_0	K	Viscosity parameter	Young modules (N/mm^2)	Poisson Ratio
36	0.1	1.16	0.667	0	32000	0.2

2.2 Steel reinforcement

As illustrated in Figure 1, 8 mm bar diameter was employed as a primary reinforcement, while 6 mm bar was employed as stirrups. Embedded region constraint was used to embed inside the concrete in the presence of steel reinforcement. The Poisson's ratio and elasticity modulus were 0.3 and 200GPa, respectively

2.3. Steel plates

At the two ends of the model (top and bottom), two steel plates with dimensions of (220×120×20) mm in length, breadth, and height were used. The Poisson's ratio and elastic modulus for the plates were and 0.3 and 200 GPa, respectively. Figure 1. shows how tie constraints were used to attach the plates to the concrete surfaces.

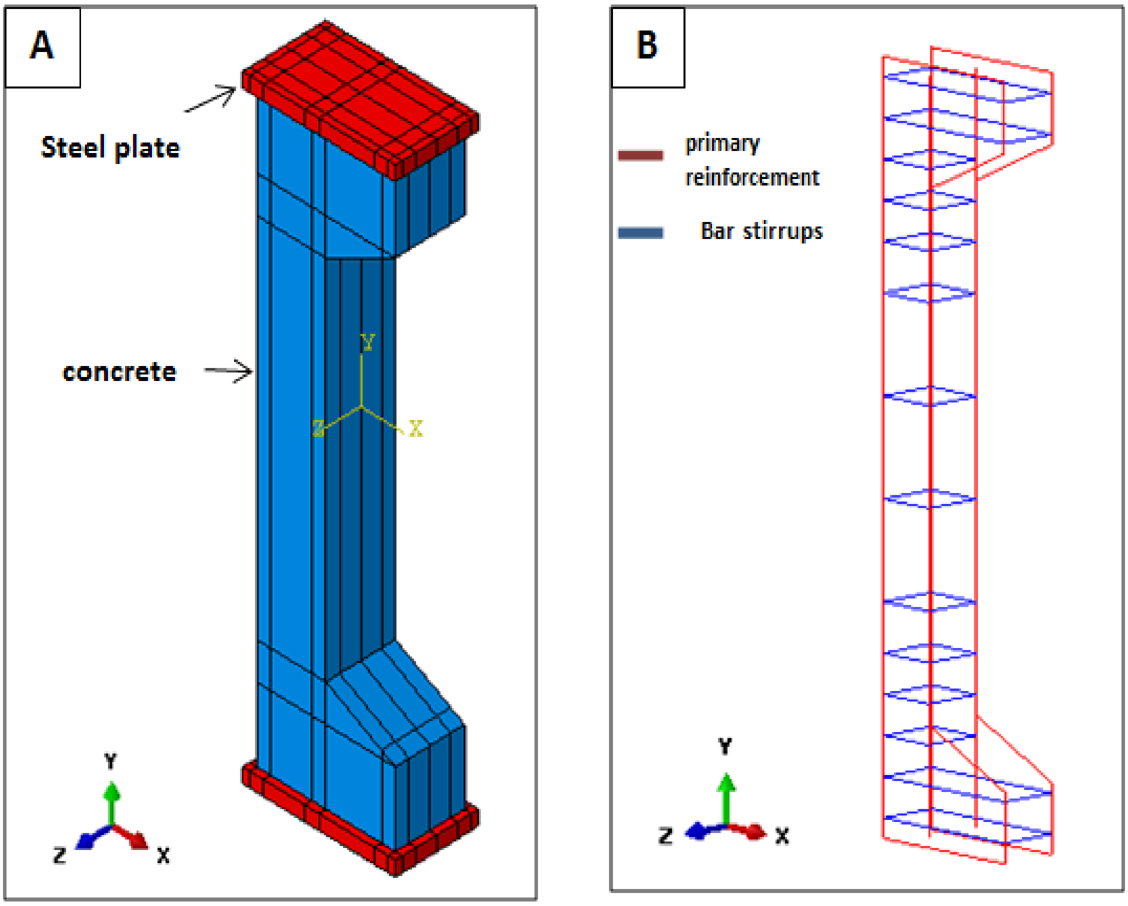


Figure 1 The materials used (A) Concrete and steel plates (B) Steel reinforcement

2.4. Carbon Fiber Reinforcement Polymer Sheets

Tie restraint was utilized to tie the CFRP with the concrete in the specimens strengthened by wrapping CFRP sheets. Besides, the CFRP sheets have been treated as a linearly elastic material to select the lamina later from the elastic behavior and model as a shell element. Figure 2 shows the CFRP laminate sizes arrangement.

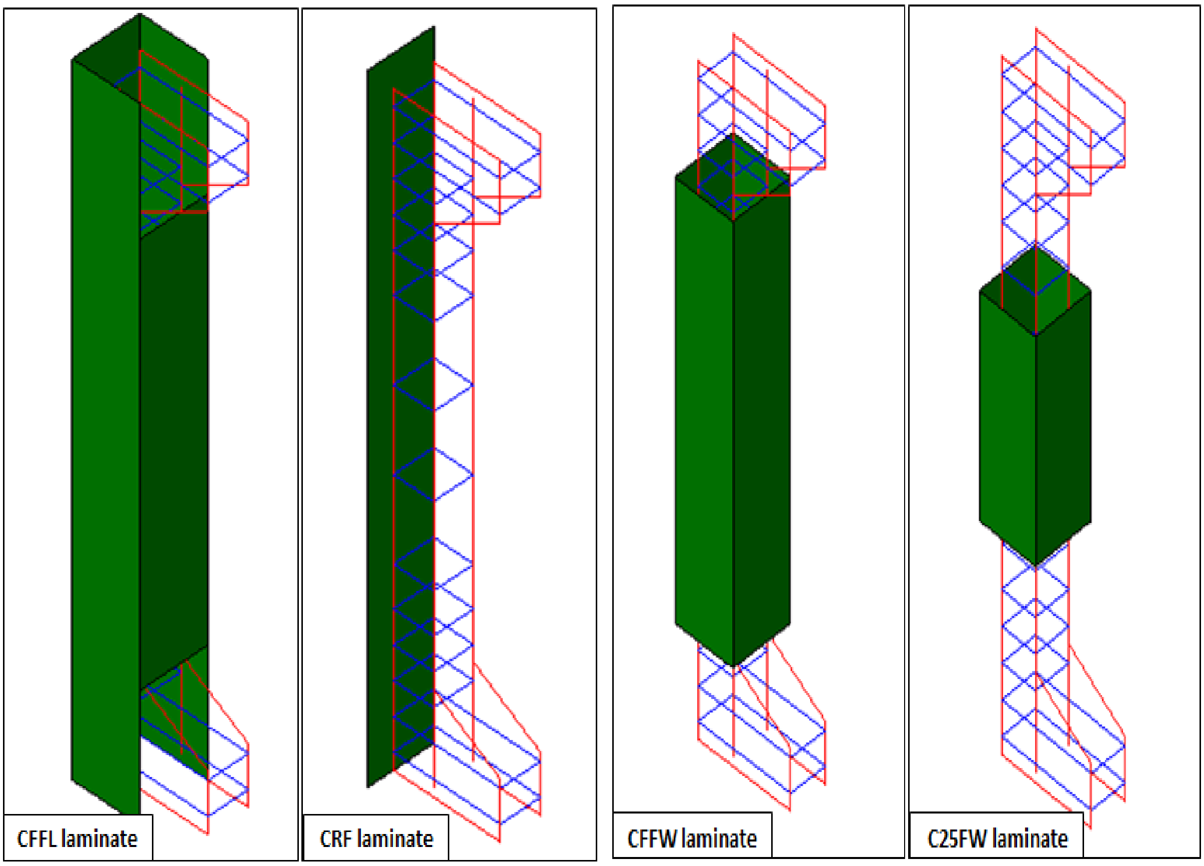


Figure 2 CFRP laminate sizes arrangement

3. Load application sequence

The partially loaded columns comprise three phases of loading in which the first phase presents the loading of the column to a specific ratio of the ultimate load. At the same time, the second phase involved removing the load from the column, which is implemented by the restart analysis. The last phase, on the other hand, included loading the column until failure after implementation of the strengthening techniques for each specimen in which the second phase stresses are inserted into the third phase from the initial step for the last one. Besides, the control column (undamaged column) included only one phase, which presents the loading of the column until failure. Loading stage and boundary condition loads were applied on steel plates of each specimen that be used are similar to the experimental work [11]. The loads were applied on a steel plate with dimensions of (220×120×20) mm with an eccentricity of 50 mm from the center, which is located at the down of the column to transform the loads to it. All reinforced concrete columns models were constrained using boundary conditions displacement to get the most appropriate solution. Besides, all samples were constrained along the line in the top plate of the column with the same 50 mm deviation from the center ((Uz = Uy = Ux = 0), as shown in Fig. 3.

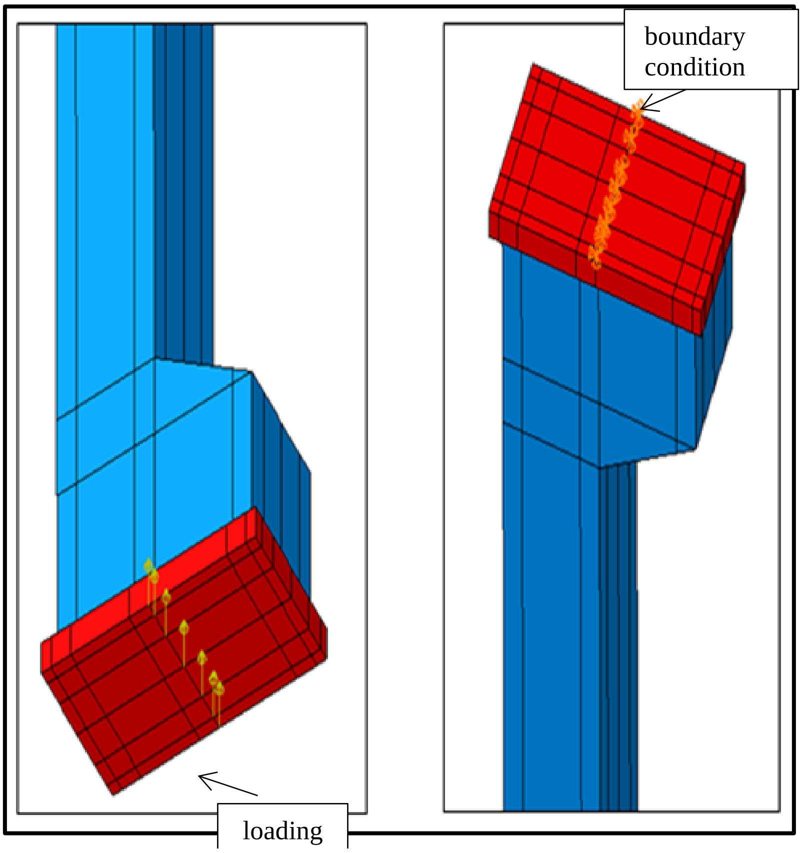


Figure 3 Loading and boundary condition for the models

4. Stress-Strain Relationship

The model of the stress-strain relationship given in [12] for the high strength concrete in the compression behaviour was used in this research. Table 3, and Figure 4. provide the data and the stress-strain relationship model used in this research, respectively.

Table 2 The stress-strain relationship used in this research [12]

Number	Yield stress (MPa)	Plastic strain (mm)
1	0	0
2	20.48	0.0001141
3	41.65	0.0003521
4	58.25	0.0008094
5	69.02	0.001501
6	68.95	0.002154
7	63.55	0.002695
8	57.25	0.003085
9	35.54	0.004105
10	15.55	0.004995
11	8.25	0.005314

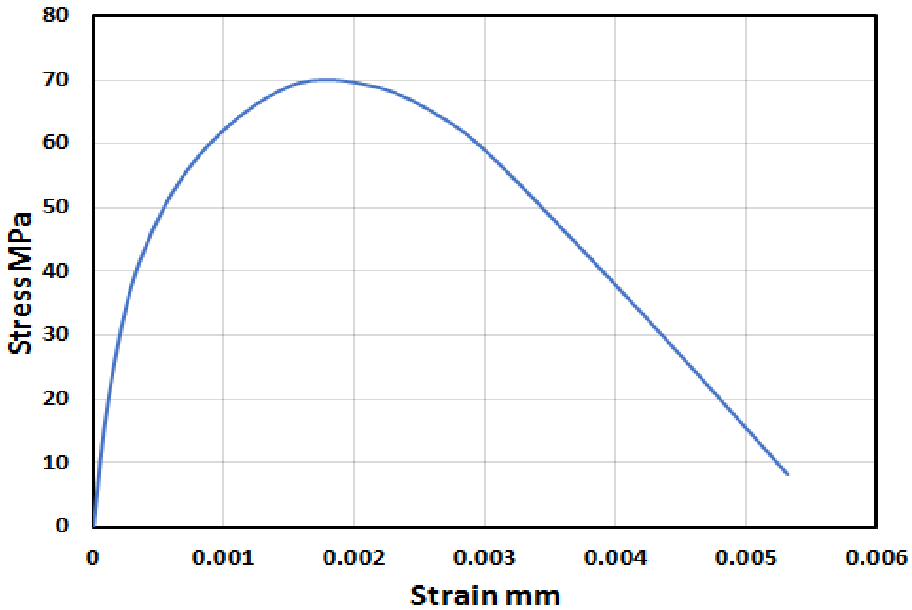


Figure 4 Model of stress-strain relationship used in this research [12]

5. Meshing

The purpose of employing several mesh sizes in ABAQUS was to conduct a convergence study to discover the optimal volume that provides the required precision. The ultimate load capacity for each mesh size is listed in Table 4. It can be seen that for mesh size 20 mm, the ultimate load and vertical deflection values were nearly 153.78KN and 2.589 mm, respectively. These numbers are fairly close to the ones obtained from the experiment (145, 2.65) [11]. In this paper, a mesh size of 20 mm was chosen. Figure 5. shown the impact of the element size on vertical load-deflection curves.

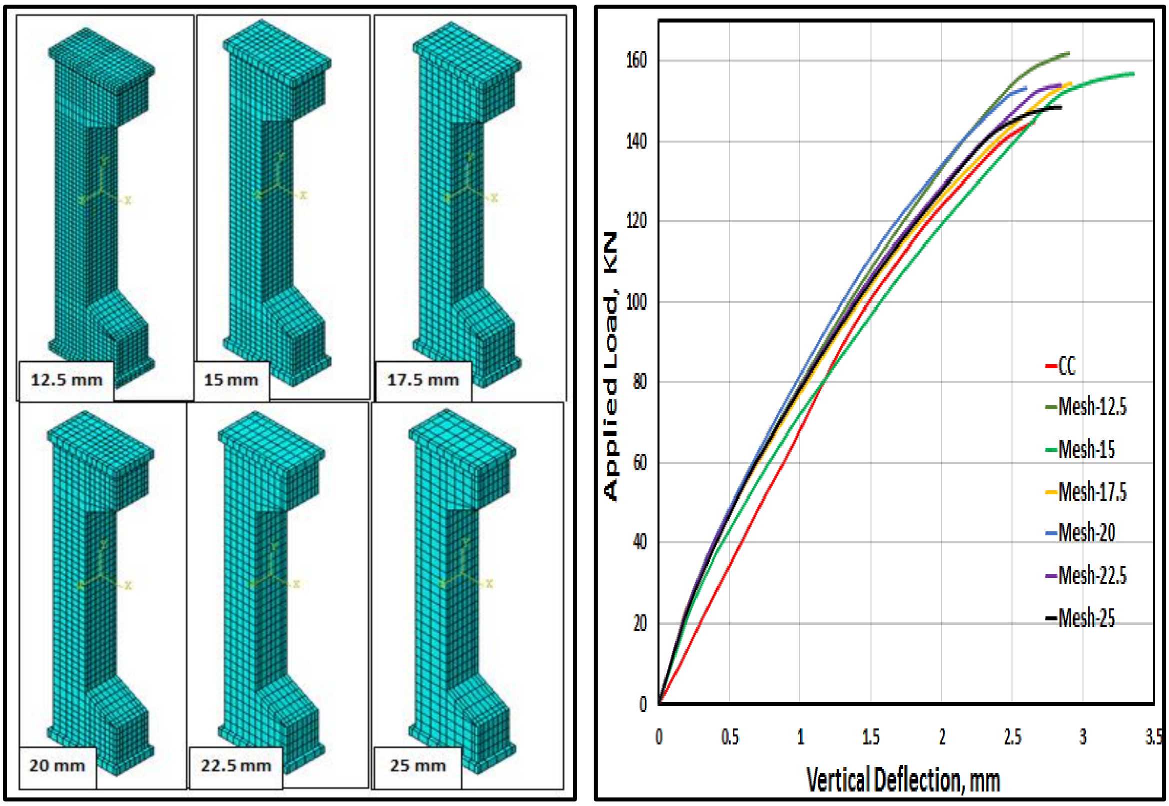


Figure 5 (A) Finite element mesh density. (B) The impact of the element size on vertical load-deflection curves

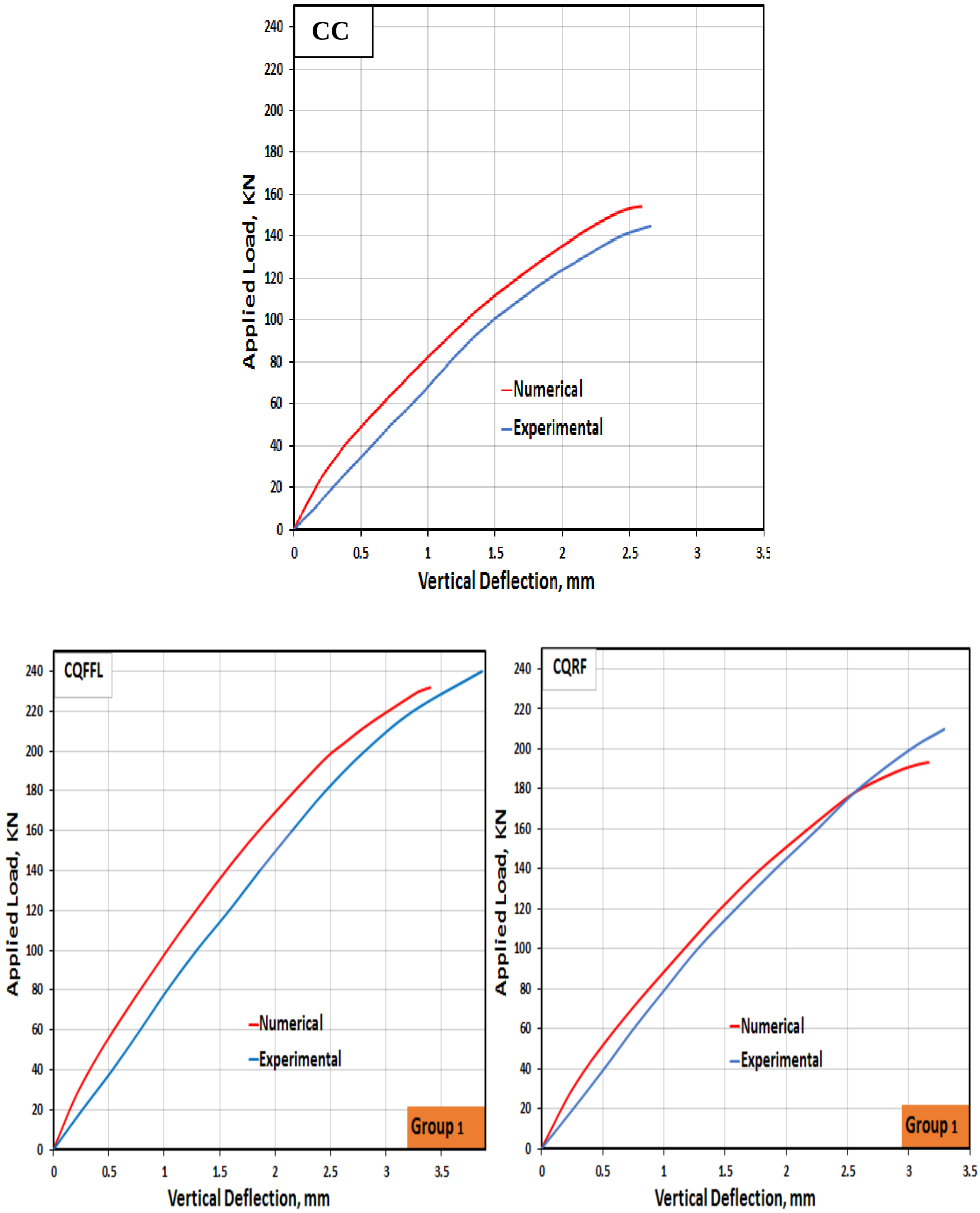
Table 4 The impact of mesh size on the ultimate capacity and vertical load-deflection values

Mesh size mm		Ultimate load KN	Vertical deflection mm
12.5	Exp	145	2.65
	FEA	161.85	2.92
15	Exp	145	2.65
	FEA	156.75	3.35
17.5	Exp	145	2.65
	FEA	154.33	2.92
20	Exp	145	2.65
	FEA	153.78	2.58
22.5	Exp	145	2.65
	FEA	153.92	2.84
25	Exp	145	2.65
	FEA	154.92	2.96

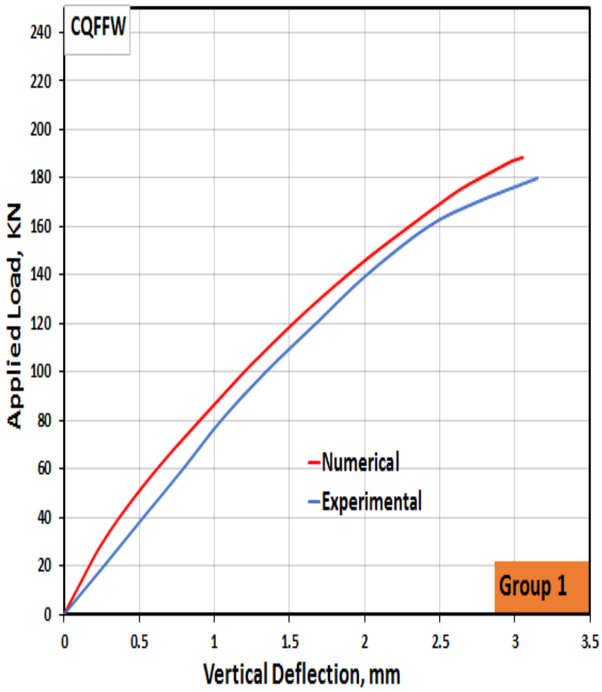
6. Finite element analysis results and discussion

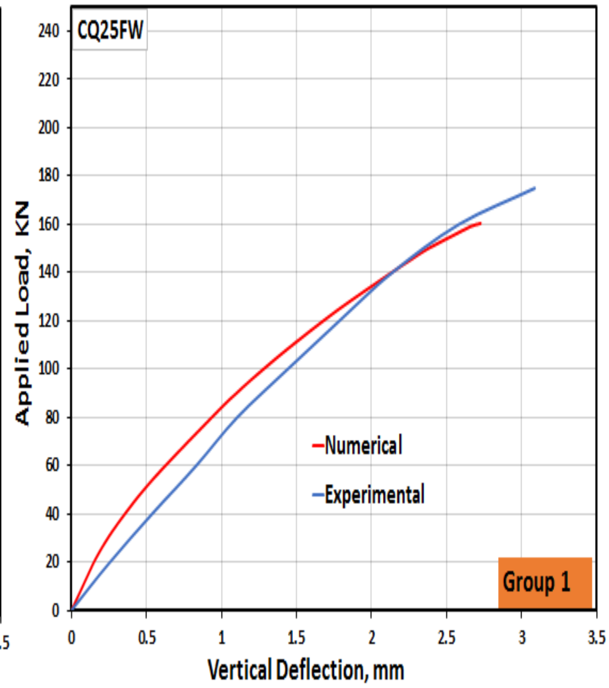
6.1 The verification work

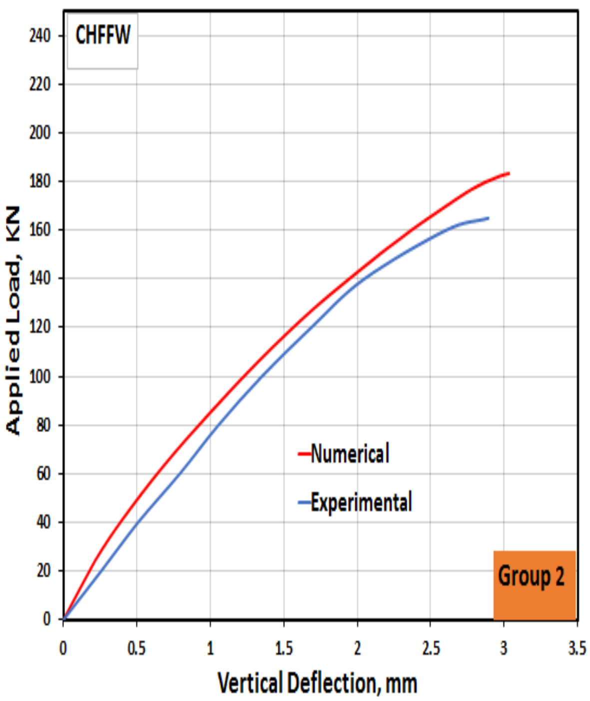
ABAQUS software was used to model and investigate all columns enhanced with CFRP techniques (Table 1) [11]. Figure 6. illustrated the difference between vertical-load deflections curves of the experimental [11] and FEM. The vertical deflections were measured at the top edge for all tested columns in a similar way in the experimental tests. The comparison showed the validity of the numerical analysis by ABAQUS with the experimental results.

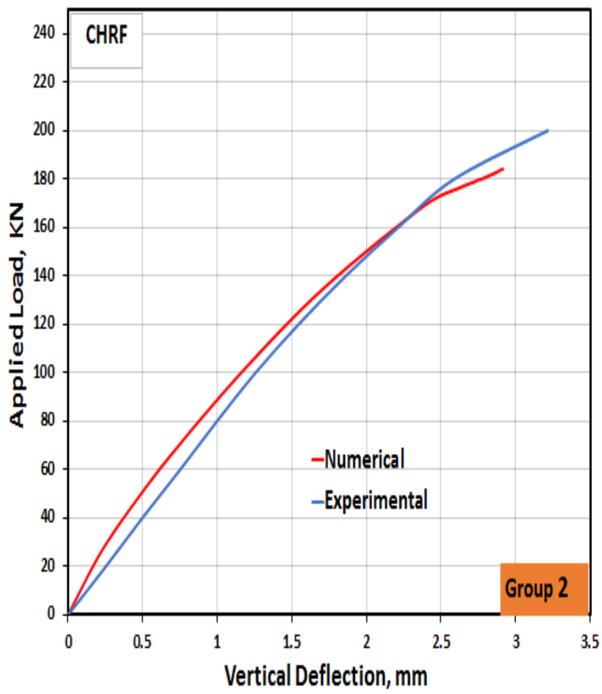


CC
Applied Load, KN
Vertical Deflection, mm
Numerical
Experimental
CQFFL
Applied Load, KN
Vertical Deflection, mm
Numerical
Experimental
Group 1
CQRF
Applied Load, KN
Vertical Deflection, mm
Numerical
Experimental
Group 1


CQFFW
Applied Load, KN
Vertical Deflection, mm
Numerical
Experimental
Group 1


CQ25FW
Applied Load, KN
Vertical Deflection, mm
Numerical
Experimental
Group 1


CHFFW
Applied Load, KN
Vertical Deflection, mm
Numerical
Experimental
Group 2


CHRF
Applied Load, KN
Vertical Deflection, mm
Numerical
Experimental
Group 2

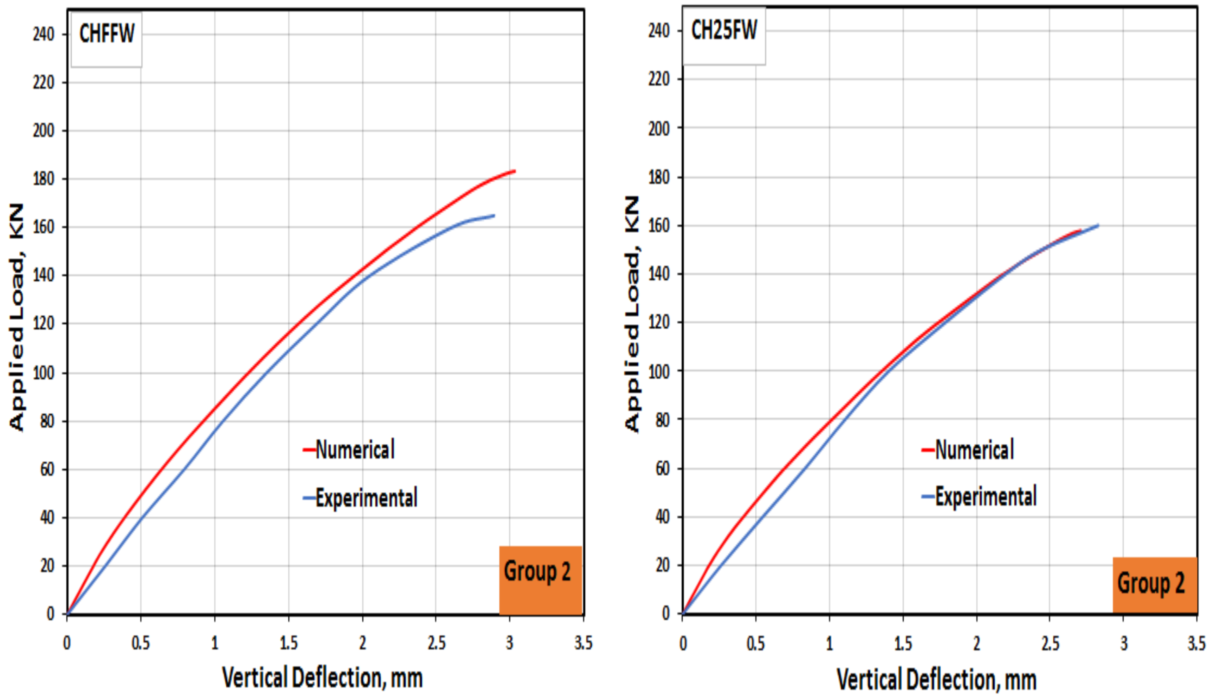


Figure 6 The numerical and experimental curves for the columns

6.2 Ultimate capacity and deflection

Table 5. presented a comparison between the ultimate experimental value of ultimate load and displacement [11] with the numerical ultimate load capacity and vertical deflection from the ABAQUS program. The maximum difference values for the strength capacity and deformation between the experimental and the numerical outcome were 6.28% and 6.24, respectively. Therefore, an excellent convergence was recorded between the numerical and experimental results. For this reason, the proposed model could be considered accurate and can be used with confidence.

Table 5. Theoretical and experimental results for tested columns

Group No.	Specimen symbol		Ultimate load (Pu) KN	Difference percentage in ultimate load, %	Vertical deflection (Δu) mm	Difference percentage in displacement, %
	CC	EXP	145	5.63	2.65	2.36
		FEA	153.17		2.58	
Group 1	CQFFL	EXP	240	3.54	3.86	13.49
		FEA	231.78		3.40	
	CQRF	EXP	210	8.65	3.29	4.01
		FEA	193.27		3.16	
	CQFFW	EXP	180	4.69	3.15	0.41
		FEA	188.45		3.05	
	CQ25FW	EXP	175	7.51	3.08	12.27
		FEA	162.78		2.73	
Group 2	CHFFL	EXP	210	5.67	3.36	1.11
		FEA	221.92		3.32	
	CHRF	EXP	200	8.68	3.21	10.27
		FEA	184.01		2.91	
	CHFFW	EXP	165	9.70	2.89	8.37
		FEA	181.36		3.03	
	CH25FW	EXP	160	2.45	2.82	3.94
		FEA	156.16		2.71	
	Mean Diff.		-	6.28		6.24

6.3 Failure modes

Two failures shapes were found for the unstrengthen control column, and the other samples strengthened with CFRP sheets. The first failure was due to concrete crushing (compression failure of concrete), While the second failure was due to the rupture of CFRP sheets, as illustrated in Figure 7.

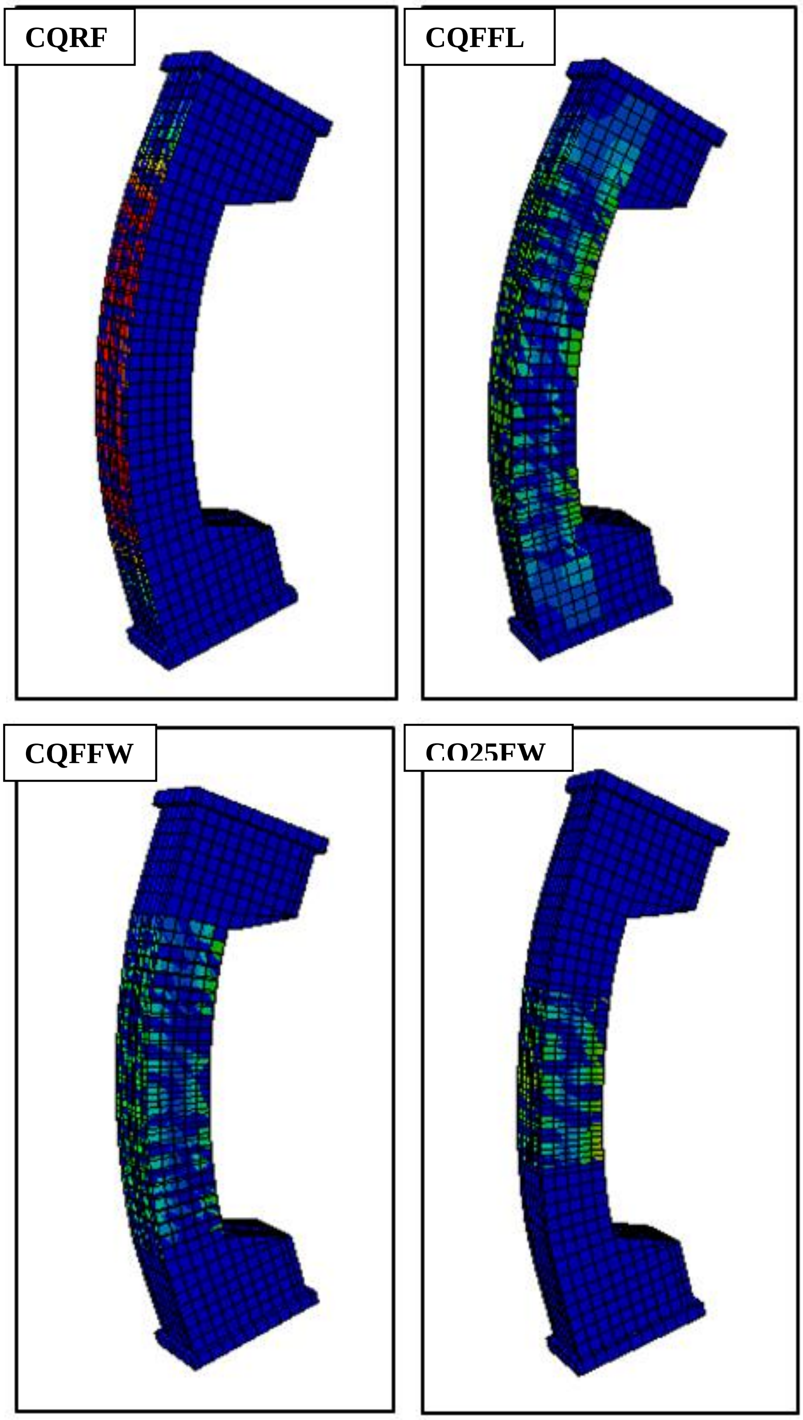


Figure 7 Failure shapes of CFRP laminate for specimens CQFFL, CQRF, CQFFW and CQ25FW.

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6.4 The distribution of the stress of CFRP sheets for specimens

Figure 8 shows the stresses distribution of the samples CQFFL,CQFF, CQFFW and CQ25FW, near the interface between CFRP and concrete. Through the results, numerical it was found that the specimens completely strengthened in the longitudinal direction (i.e CQFFL, CQRF) have greater stresses than the specimens strengthened in the transverse direction (i.e CQFFW, CQ25FW).

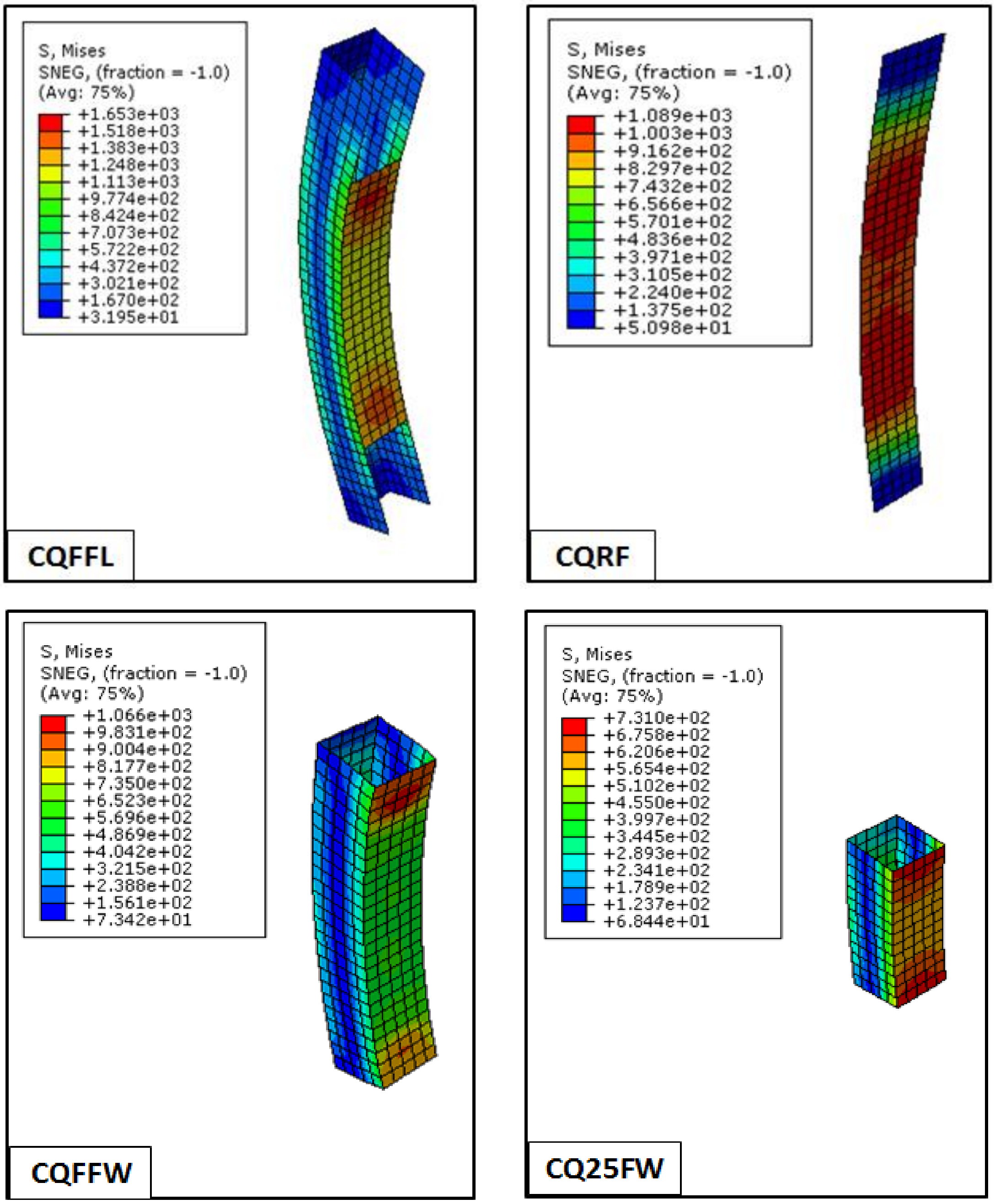

Figure 8. The distribution of the stress between CFRP laminate and concrete for specimens CQFFL, CQRF, CQFFW and CQ25FW.

8. Paramtric study

Several vital parameters were proposed to be investigated numerically to study their impact on the behavior of HSC damaged columns with a squared cross section under eccentricity loads by an eccentricity of 50 mm from the center (e/h = 0.5), These parameters included increase the number of CFRP sheets for specimens strengthened, the impact of various eccentricity loads (e/h) and the impact of increasing the initial loading ratios for specimens strengthened.

8.1 Increasing the number of CFRP layers

The load-vertical deflections for specimens CQFFL, CQFFW, CHRF, and CH25FW that were strengthened with one, two, and three layers of CFRP sheets are shown in Figure 9.

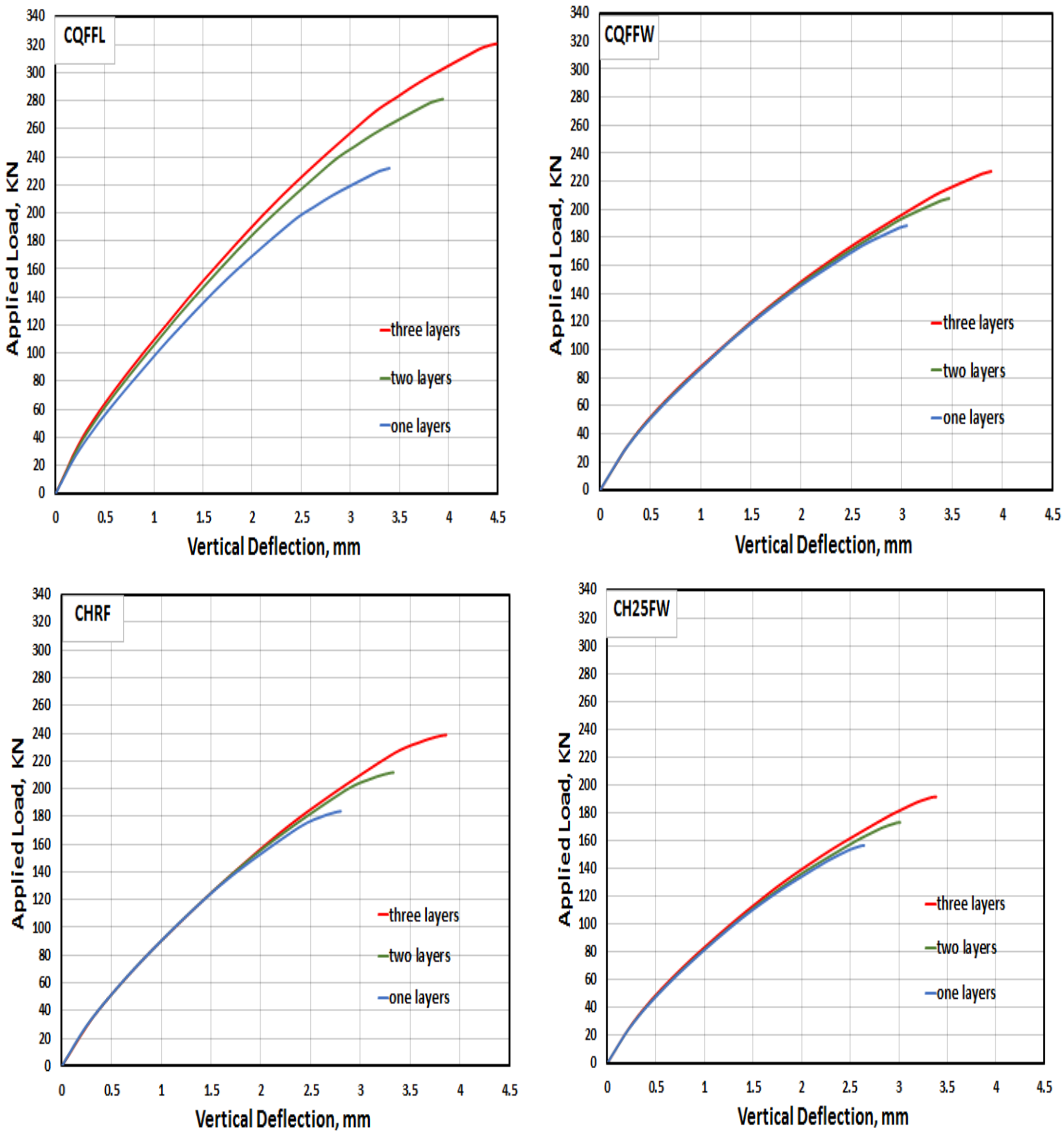

Figure 9 Effect the number of layers for CQFEL, CQFFW, CHRF and CQ25FW specimens

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in which the figure explained the impact of increasing CFRP layers. There was a slight improvement in the load capacity and deflection, which is the main noticed observation from figures of the specimens CHRF and CH25FW. On the other hand, the samples of CQFFL and CQFFW exhibited a remarkable improvement in their ultimate load capacity. The values of the ultimate load capacity for CQFFL when using one, two and three layers of CFRP sheets were (231.78, 280.43, 320.82) KN, respectively. Furthermore, the values of the load capacity for CQFFW when using one, two, and three layers of CFRP sheets were (188.45, 208.11, 226.85) KN, respectively. Table 6. shows the impact of the number of sheets of CFRP.

Table 6 Effect of numbers of CFRP layers

Column symbol	Strengthening Scheme	Ultimate Load KN	Increment Ratio %	Vertical deflection mm
CQFFL	Full longitudinal wrapping with CFRP for all column faces - One layer	231.78	-	3.401
	Full longitudinal wrapping with CFRP for all column faces - Two layers	280.43	20.98	3.944
	Full longitudinal wrapping with CFRP for all column faces - Three layers	320.82	38.41	4.488
CQFFW	Full longitudinal wrapping with CFRP for all column faces - One layer	188.45	-	3.05
	Full longitudinal wrapping with CFRP for all column faces - Two layers	208.11	10.43	3.47
	Full longitudinal wrapping with CFRP for all column faces - Three layers	226.85	20.37	3.891
CHRF	Full longitudinal wrapping with CFRP for rear face only -One layers	184.01	-	2.914
	Full longitudinal wrapping with CFRP for rear face only - Two layers	213.95	16.27	3.334
	Full longitudinal wrapping with CFRP for rear face only -Three layers	238.21	29.45	3.864
CH25FW	Horizontal wrapping with CFRP for 250 mm length at column mid-height -One layer	156.16	-	2.713
	Horizontal wrapping with CFRP for 250 mm length at column mid-height - Two layers	173.66	11.20	3.016
	Horizontal wrapping with CFRP for 250 mm length at column mid-height - Three layers	188.13	20.47	3.385

8.1 Various eccentricity load e/h

The impact of changing the load eccentricity on the load capacity and load-vertical deflection of square partially damaged HSC columns for the specimens of CQFFL and CQRF were examined. The studied eccentricity load(e/h) were (0.35, 0.5, 0.7) with fixed all other factors such as the number of CFRP layers and spacing between the CFRP sheets. Figure 10. presented the load-vertical deflections for specimens with various eccentricity load(e/h). Furthermore, changing the eccentric load of the sample CQFFL at a deflection of (e/h= 0.35) gave an increase in the maximum amplitude compared to the deflections of (e/h=0.5, 0.7) by (311.25, 231.78, 119.78) KN, respectively. Table 7. presented the numerical results for the effect of eccentric load for the specimens CQFFL and CQRF.

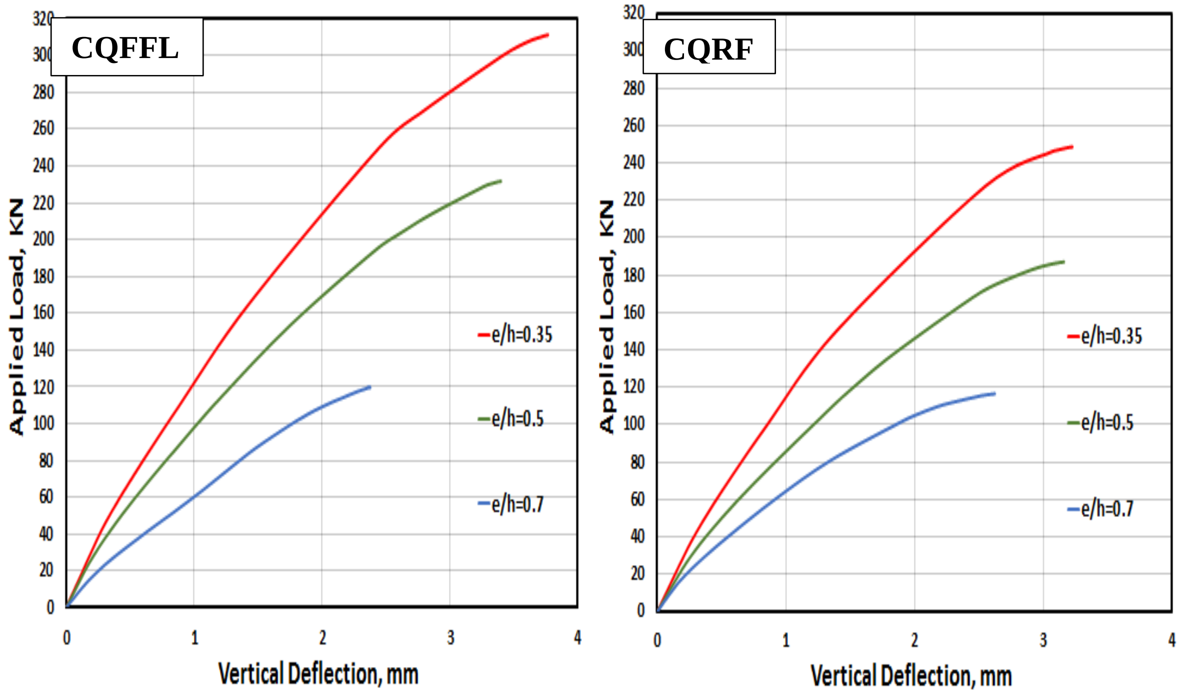


Figure 10 Effect of various eccentricity load e/h for the load- vertical deflection curves for CQFFL and CQRF comparing with e/h=0.5.

Table 7 Effect of changing eccentricity load e/h for CC, CQFFL and CQRF

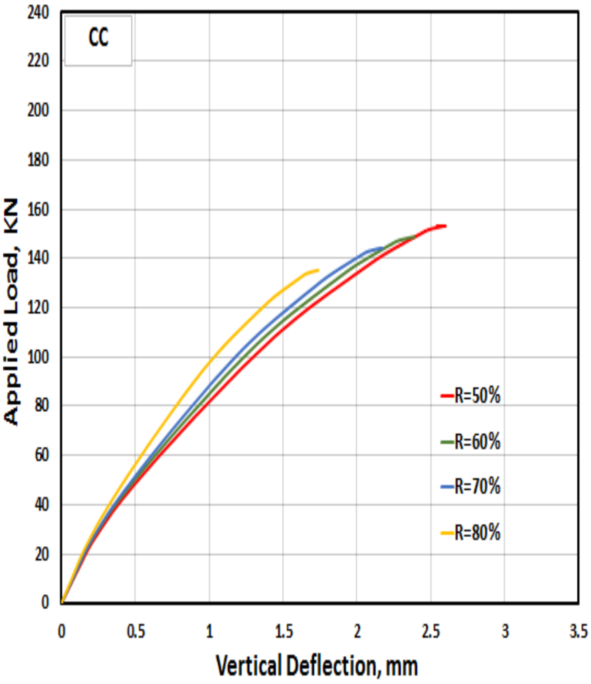
Column symbol	e/h	Ultimate load KN	Decreasing Ratio %	Vertical Deflection (mm)
CQFFL	0.35	311.25	34.28	3.768
	0.5	231.78	……..	3.401
	0.7	119.78	-48.32	2.356
CQRF	0.35	249.52	29.10	3.227
	0.5	193.27	……..	3.162
	0.7	116.43	-39.75	2.625

5.3. Various Initial Loading Percentage

The second load percentage was 50 % of the ultimate load, which was changed to the followed rates (60, 70, 80)%. These percentages were studied for the specimens of CC and CQFFL. Figure 11. illustrated load- vertical deflection curves for the effect of variation the rate of loading for CC and CQFFL. From the results, it clear that increasing the rate of initial loading from (50-80)% led to a decrease in the values of the maximum strength capacity and deformation. The load strength for CC and CQFFL were (138.94and 195.45) KN, respectively. In contrast, the vertical deflection values decreased to (1.738and 2.309) mm, respectively, for the specimens mentioned above, as shown in Table 7.

Table 8 Effect of various loading percentage for CC and CQFFL

Column symbol	Loading ratio %	Ultimate load KN	Decreasing Ratio %	Vertical deflection (mm)
CC	0.5	153.17	……..	2.54
	0.6	148.66	2.94	2.38
	0.7	144.15	5.88	2.17
	0.8	138.94	9.23	1.73
CQFFL	0.5	221.92	…….	3.32
	0.6	212.05	4.43	2.85
	0.7	204.20	7.98	2.69
	0.8	195.45	11.92	2.31



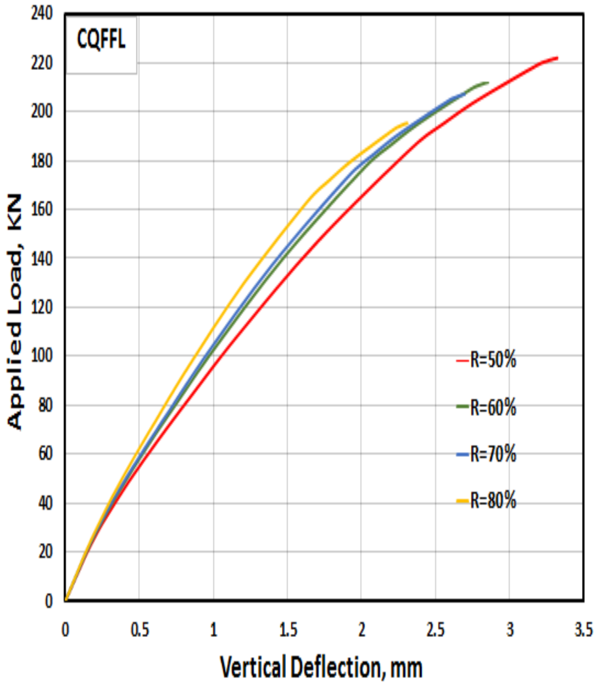


Figure 11 Effect of change the initial load ratio for CC and CQFFL comparing with initial load ratio at 50% of the ultimate load.

9. Conclusions

1. The findings of the maximum strength capacity and displacement between the laboratory and numerical of all specimens were matched, indicating that the numerical solution's results are valid.
2. Results showed that the effect of increasing the numbers of CFRP layers on the strength ultimate load capability was positive. For (CQFFL, CQFFW, CHRF, CH25FW), the increments were (20.98, 38.41) %, (10.43, 20.37) %, (16.27, 29.45), and (11.20, 20.47), respectively when using two or three layers.
3. The ultimate load capacity increases as the eccentricity load decreases. Furthermore, changing the eccentric load of CQFFL at a deflection of (e/h= 0.35) gave a rise in the maximum strength capacity compared to the deflections of (e/h=0.5, 0.7) by (311.25, 231.78, 119.78) KN, respectively.
4. The loading ratio was found to have an inverse relationship with the ultimate load capacity, as rising the loading ratio from 50 per cent to 80 per cent reduced the final load capacity, as the last load capacity decreases by 9.23 and 11.92 % for CC and CQFFL, respectively when the loading percentage was increased by 80 per cent.,

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التحقيق العددي للسلوك الإنشائي للأعمدة الخرسانية عالية القوة المحملة جزئيًا تحت التحميل احادي المحور

الخلاصة: *يهدف هذا البحث إلى دراسة عددية والتحقق من صحة نموذج رقمي للسلوك الإنشائي للأعمدة المربعة المحملة جزئياً من الخرسانة المسلحة عالية القوة (HSC) مع انحراف 50 ملم من المركز (e / h = 0.5) باستخدام ABAQUS. لهذا الغرض ، تم استخدام تسعة أعمدة HSC قصيرة بعد تقويتها بألواح البوليمر المقوى بألياف الكربون (CFRP) في مخططات مختلفة واختبارها تجريبيًا من حيث قوتها النهائية والاستجابة الكاملة لانحرافات الحمل الرأسية التي تم الحصول عليها من ورقة بحثية سابقة قيد النشر لاستخدامها للتحقق من سلامة النتائج الحسابية. تم بعد ذلك التحقق من المعاملات الإضافية باستخدام النموذج الذي تم التحقق منه ، مثل تأثير زيادة طبقات CFRP ، الانحرافات المختلفة للحمل (e / h) ، وزيادة نسب التحميل الأولية. من خلال التقارب في قيم كل من الحمل النهائي والانحرافات ، أظهر التحليل العددي مستوى عالٍ من التوافق مع النتائج التجريبية. أظهرت النتائج أيضًا أن زيادة عدد صفائح البلاستيك المقوى بألياف الكربون (CFRP) للعينات المقواة بشكل شامل باستخدام شرائط CFRP في كلا الاتجاهين العرضي والطولي زاد بشكل كبير من سعة الحمل القصوى. في الوقت نفسه ، من خلال تقليل نسبة الانحراف (e / h) ، تم تعزيز القوة القصوى والانحرافات لجميع العينات المعززة كليًا أو جزئيًا بألواح CFRP. في الواقع ، أظهرت النتائج أن زيادة نسب التحميل الأولية للعينات المقواة أدى إلى انخفاض في الحمل النهائي.*