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Simulation of the behaviour of RC columns strengthen with CFRP under rapid loading

Soheil Esfandiari[*1] and Javad Esfandiari[2a]

[1]*Department of Civil Engineering, College of Engineering, Sistan and Balouchestan University, Daneshgah Street-Zahedan, Iran*
[2]*Department of Civil Engineering, College of Engineering, Kermanshah Branch, Islamic Azad University Kermanshah, Iran*

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Abstract. In most cases strengthening reinforced concrete columns exposed to high strain rate is to be expected especially within weak designed structures. A special type of loading is instantaneous loading. Rapid loading can be observed in structural columns exposed to axial loads (e.g., caused by the weight of the upper floors during a vertical earthquake and loads caused by damage and collapse of upper floors and pillars of bridges).Subsequently, this study examines the behavior of reinforced concrete columns under rapid loading so as to understand patterns of failure mechanism, failure capacity and strain rate using finite element code. And examines the behavior of reinforced concrete columns at different support conditions and various loading rate, where the concrete columns were reinforced using various counts of FRP (Fiber Reinforcement Polymer) layers with different lengths. The results were compared against other experimental outcomes and the CEB-FIP formula code for considering the dynamic strength increasing factor for concrete materials. This study reveals that the finite element behavior and failure mode, where the results show that the bearing capacity increased with increasing the loading rate. CFRP layers increased the bearing capacity by 20% and also increased the strain capacity by 50% through confining the concrete.

Keywords: reinforced concrete column; failure; rapid loading; axial load; CFRP

1. Introduction

According to the American Concrete Institute (ACI), concrete with 50MPa is considered to High Strength Concrete (HSC), and when reinforced in concrete columns, they become the main structural members designed to transfer gravitational forces and the weight of floors (Austrian Building Code 2008). Loads that are quickly exerted on the column axis (e.g., hits) are known to cause major damage to the structure. Typical structural damages are those occurred during earthquakes where the damaging waves specifically move in the vertical direction. S and Rayleigh waves are the main waves that immediately transfer strong forces to the structure by vertical movements using the structural weight. For example, the effect of rapid loads can be seen in the Bam earthquake of 2003, Iran, where the vertical component and severe upward and downward

∗Corresponding author, Master of Structure, E-mail: esfandiari.soheil@yahoo.com
[a]Assistant Professor, E-mail: J.esfandiari@iauksh.ac.ir

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displacements created other forces causing more damage to the buildings and structures and killing some 27,000 people.

Subsequently the results of this paper argues that if we can strengthen up to 20% of the columns with four CFRP layers, that this will prevent damage similar to that of the Bam earthquake.

Acquiring knowledge of the forces exerted on the columns and behavior of concrete columns under special loadings has been studied by several scientists in recent years. Abram (1917) proved that the concrete strength increases with increasing the strain rate. Bischoff and Perry (1991) and Malvar and Rose (1998) found that the strain rate plays an important role in the behavior of reinforced concrete columns under dynamic and rapid loads. Reinschmidt *et al.* (1964) and Iwai *et al.* (1988) studied the behavior of columns under rapid loading, where the results showed that increased pressure leads to increased strain. According to Berto (1972), for a rigid structure with a period of about 0.1 s, the strain rate in some specific areas of the structure can reach more than 0.025 s-1. According to Pajak (2011) the rates of various loading types are as follows Fig. 1.

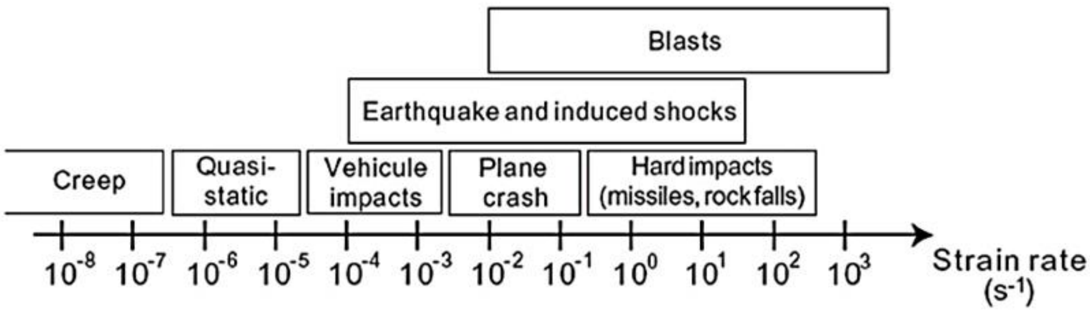


Fig. 1 The rates of various loading types (Pajak 2011)

Where: S^{-1} is rate per second

There have been other studies on the behavior of 60 reinforced concrete columns under constant and rapid horizontal loads perpendicular to the column axis, advocating that this specific type of damage should be studied further so as to recognizing the failure pattern and what needs to be done in order to strengthen the columns (Orozco 2002, Taghami 2005, and Li *et al*. 2016). Understanding the behavior of reinforced concrete columns under rapid loading is of great importance.

2. Relations provided by regulations and codes

The maximum strength of the column is calculated based on strength and stability. In the situation where the column is affected by local buckling, the relation offered by AASHTO[†] (2012) and CEB-FIP[‡] (1990) for reinforced concrete components under pressure is presented by Eq. (1)

[†]American Association of State Highway and Transportation Officials
[‡]Comite Euro–International Du Beton

$$P_r = \varphi P_n \tag{1}$$

Where *Pn* for static and dynamic loading of mixed members is obtained by Eqs. (2) and (3) respectively

$$P_{sn}=0.85f_{sc}(A_g\text{-}A_{st})+f_{sy}A_{st} \tag{2}$$

$$P_{dn}=0.85f_{dc}(A_g\text{-}A_{st})+f_{dy}A_{st} \tag{3}$$

Finally, Dynamic Increase Factor (DIF) calculated using the Eqs. (2) and (3)

$$DIF=\frac{P_{dn}}{P_{sn}} \tag{4}$$

The strength coefficients are defined as follows:

φ: The reduced resistance coefficient applicable for concrete. Given the placement and no centrality, it is equal to 0.9 for reinforced concrete sections with internal tension control (according to AASHTO-LRFD)[§].

f_{dc}, f_{sc}: The dynamic and static compressive strengths of concrete, respectively (MPa).

f_{dy}, f_{sy}: The dynamic and static compressive yield strength of longitudinal bars, respectively (MPa).

A_g: The overall cross sectional area (mm^2).

A_{st}: The cross sectional area of longitudinal bars (mm^2).

3. Modelling

To conduct a large number of experiments so as to evaluate the parameters affecting the behavior of columns would be costly and time consuming. Hence, simulation using finite element method can provide proper models for experiments in real scale. Simulation is believed to not have many experimental limitations and is known to give useful results (Kim 2009). In this study, finite element was used to perform simulations. To validate the finite element model by experimental results in the modeling process, the experimental assumptions provided by Zheng and Xu (2012) were used.

3.1 Sample characteristics

A reinforced concrete column with a length of 3 was used for modeling and analysis. The distance between the stirrups near the support and in the midst was 75 mm and 150 mm respectively. Fig. 2 shows the geometric dimensions of the concrete column. The column was connected to the support by rigid joints and the top and bottom of the column modeled fix in displacement and rotation.

The concrete strength is 55 MPa. The longitudinal reinforcements were made of a steel rebar with diameter of 16 mm, static yield strength of 483 MPa and static ultimate strength of 617.9 MPa.

[§]American Association of State Highway and Transportation Officials–Load Factor Design

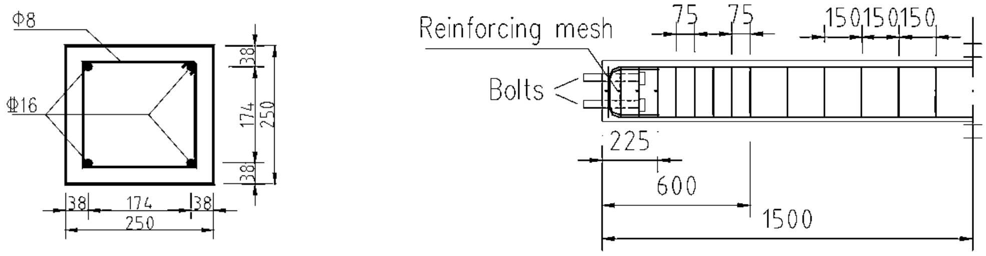


Fig. 2 The geometric dimensions of the concrete columns (Zheng and Xu 2012)

The stirrups were made of a steel rebar with a diameter of 8 mm, static yield strength of 344.6 MPa and static ultimate strength of 421.6 MPa (Zheng and Xu 2012). Two rigid plates were used at both ends of the column to prevent the column failure at stress concentration points. Numerical analysis was performed using finite element. The load was applied by controlling the displacement at both ends of the column. The concrete section was meshed by eight-node brick three dimensional with reduced integration elements (C3D8R[**]) while the rigid plate was meshed by four-node rigid three dimensional elements (R3D4[††]). The tow-node truss three dimensional elements (T3D2[‡‡]) were used to mesh reinforcements. FRP layers were meshed using the four-node shell elements S4R. Two Gauss operators were used for the intersection of two materials. The stress-strain curve of the concrete was selected according to the European Standards for Reinforced Concrete (Wee 1996). To model the behavior of concrete, the plastic concrete damage for sensitive analyses model in the ABAQUS user manual (2011) finite element library was used in Table 1.

Table 1 Plastic concrete damage parameter

Dilation angle	E	σ_{b0}/σ_{c0}	K	Viscosity parameter
45	0.1	1.16	0.666	0.0001

Where:

Dilation angel is angel between messes Precession tension and static pressure tension in Restricted tension. Note that this variable is not effective for bending forces.

E defined as: Second derivative of plasticity flow function

σ_{b0}/σ_{c0} is defined as: Ratio of maximum biaxial tension pressure to uniaxial tension pressure

Viscosity parameter defined as: For reduce sensitive of Convergence in concrete material

3.2 Column failure pattern

According to Zheng and Xu (2012), the proper failure pattern for reinforced concrete columns

[**]Eight-node brick three dimensional with reduced integration element
[††]Four-node Rigid three dimensional element
[‡‡]Tow-node truss three dimensional element

under rapid loading is the failure from the middle of column Fig. 3. This failure was due to yielding of the concrete materials in the column. Column failure and damage occur not only due to decrease in the overall stability, but due to local material yield of in the middle of the column. Analyses were performed for a loading rate of 23 mm/s.

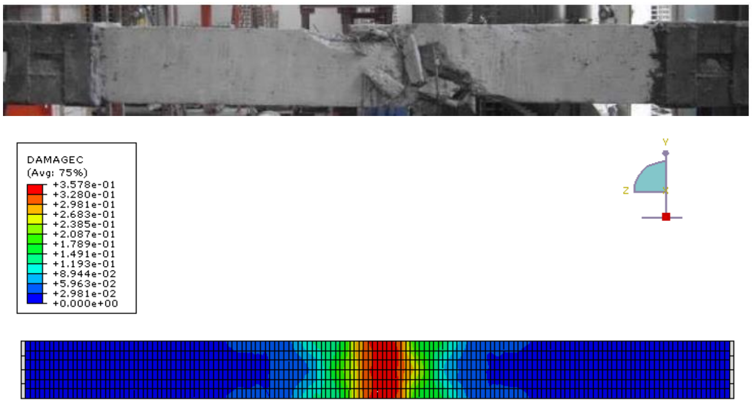
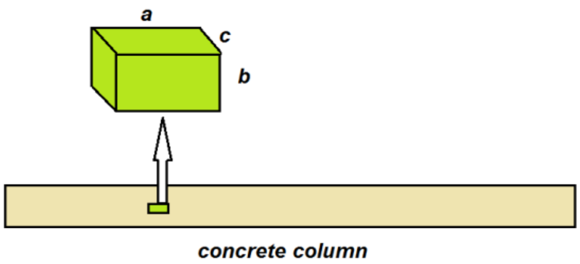


Fig. 3 Comparison of experimental and finite element results

To further examine the relative impact of element size for failure patterns and bearing capacity, sensitive analyses was performed and a fixed number of elements were considered in cross section (8 elements with a size of 3.13 Cm) while the number of elements along the column length varied. As seen in Fig. 6, the variable a, may take different values along the column length. This is shown with the ratio a/b. The variables c and b have the same length of 3.13 Cm.



a/b=0.78, element size (3.13, 3.13, 2.44)

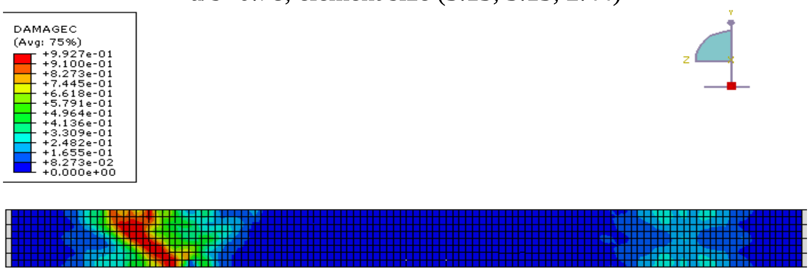
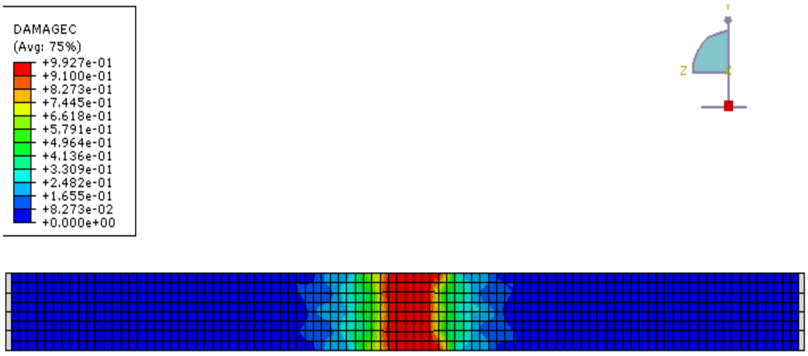
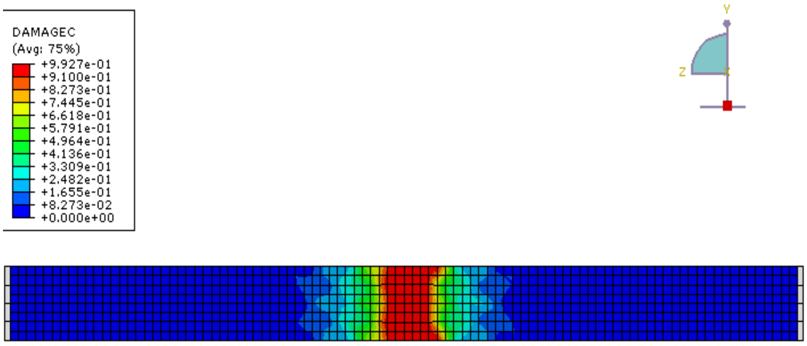


Fig. 4 Selection of the elements in compression damage to calibrate the results (a/b is aspect ratio) Where, (c,b,a) is equal to (x,y,z)

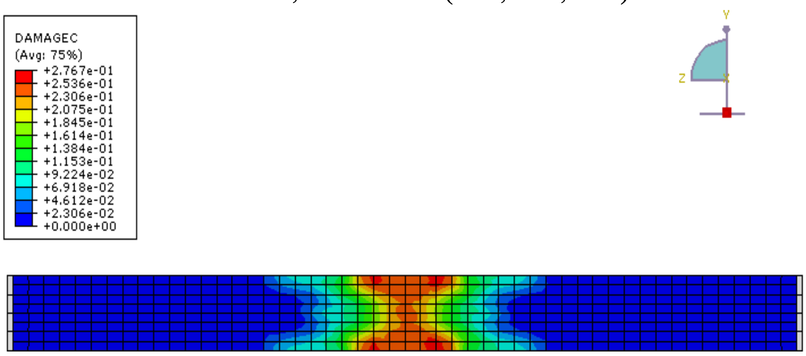
a/b=1, element size (3.13, 3.13, 3.13)



a/b=1.25, element size (3.13, 3.13, 3.91)



a/b=1.88, element size (3.13, 3.13, 5.88)



a/b=2.34, element size (3.13, 3.13, 7.32)

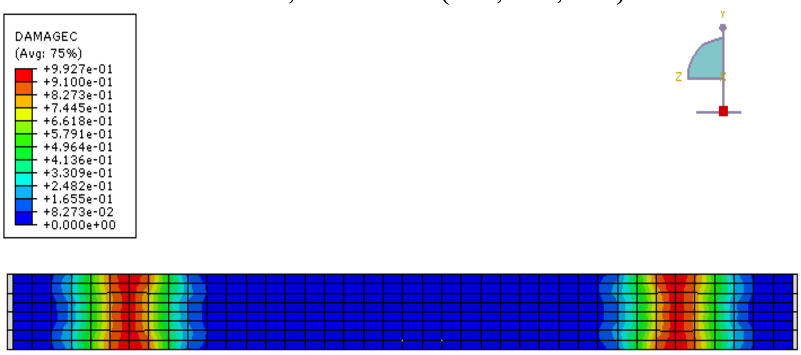


Fig. 4 Continued

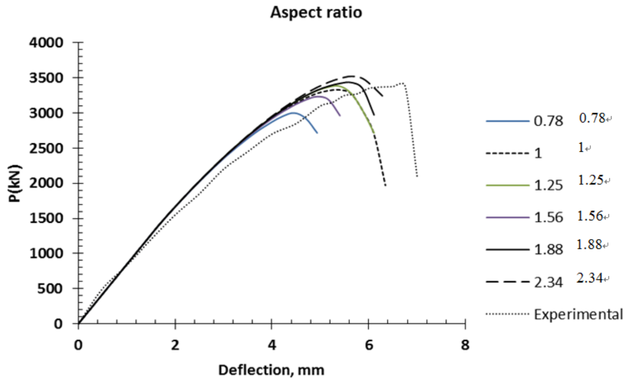


Fig. 5 Different dimensional ratios for load-deflection chart (a/b)

As shown and compare in Fig. 3 and Fig. 4, only the failure patterns with aspect ratio between 1 to 2.34 show the reasonable behavior of the reinforced concrete columns and are in good agreement with the experimental results, because the failure of concrete materials and local yield occur in the middle of the column then patterns below aspect ratio 1 and more than 2.34 are not be true. So the element size has a considerable parameter on the behavior of reinforced concrete columns due to analyses and it is due to how length of column is. Furthermore, the bearing capacities at different element sizes show that the experimental failure changes by 24% from 3000 kN for 0.78 aspect ratio to 3520 for 2.34 aspect ratio, this difference can be seen in the Fig. 5. According to the Fig. 5, just element with aspect ratio of 1.25 and 3380 kN in bearing capacity has been accepted. It is because of the maximum accuracy compare with experimental results which is less than 0.6% difference.

3.3 The column behavior under different loading rates

According to research conducted by the European Concrete Platform (ECP) (as well as the 8th Concrete Conference CEB-FIP 1990), the dynamic increase factor for the strain rates of 0.0040-0.0070 varies from 1.11 to 1.13. In this paper, the loading rates can be divided into five categories. In the first case, a displacement of 23 mm was applied to the column in a loading time of 1 s. Therefore, the strain rate will be equal to 4.3×10^{-2} by result of divide 1 sect and 23 mm. Fig. 8 shows the failure mode. A same failure pattern was obtained for other rates.

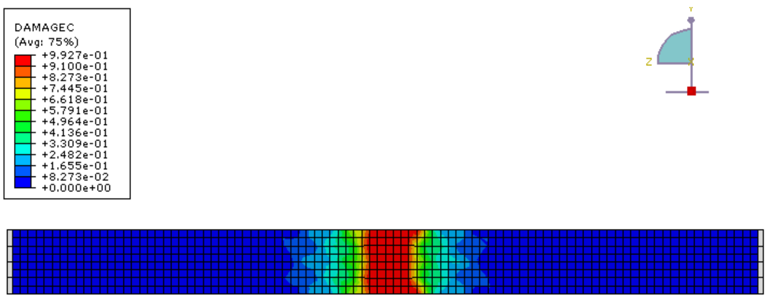


Fig. 8 The failure pattern for a strain rate of 23 mm/s

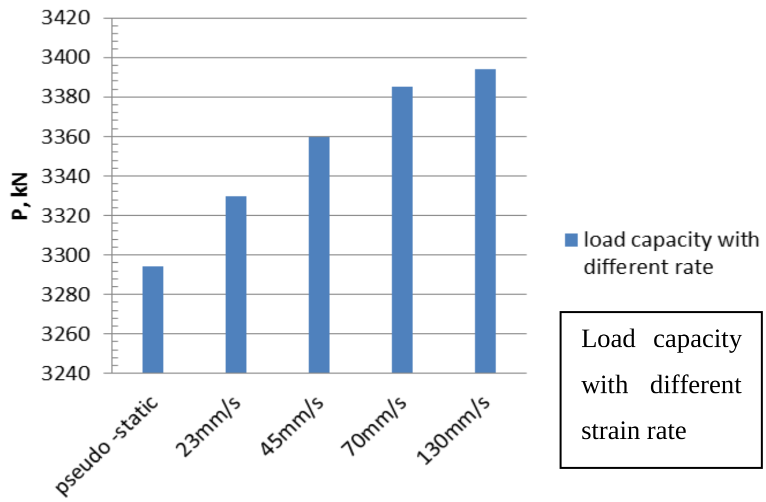


Fig. 9 The bearing capacity for different strain rates from the finite element modeling (note that pseudo-static here is from modeling and without φ factor)

As shown in Fig. 9, with increasing the strain rate in concrete materials, the dynamic bearing capacity increases. The following diagram shows different bearing capacities for different loading rates (notice that pseudo-static was given from model results with φ factor that is equal to 2964.6 kN). With increasing the strain rate from 23 to 130 mm/s, the bearing capacity increases by 64.66 (1.9% increment). Table 2 compares the numerical results. According to the above results, the proper pattern for modeling can be recognized.

Table 2 The bearing capacity and strength enhancement coefficients

Modeling results	23 mm/s	45 mm/s	70 mm/s	130 mm/s
load capacity (KN)	3329.6	3359.4	3385.3	3394.2
DIF P (modeling)	1.123153	1.133202	1.141945	1.144934
DIF D (modeling)	1.028626	1.030534	1.068702	1.087786
Deu (modeling)	5.39	5.4	5.6	5.7

Where: DIF P calculated from Force, DIF D calculated from Deflection and Deu is amount of displacement equal with Ultimate capacity.

4. The impact of effective length of the column and support conditions

Numerical analysis was performed to examine the behavior of columns at different support conditions and column effective length (K) through applying a very small displacement perpendicular to the length of the column causing an initial deviation in the overall column buckling (a same loading strain rate was applied in all finite element models).The behavior of columns depends on support conditions and column lengths were changed significantly. For short columns with full rigid supports, Eccentricity made by 5 mm deflection on perpendicular in middle of column axes due to the analyze.

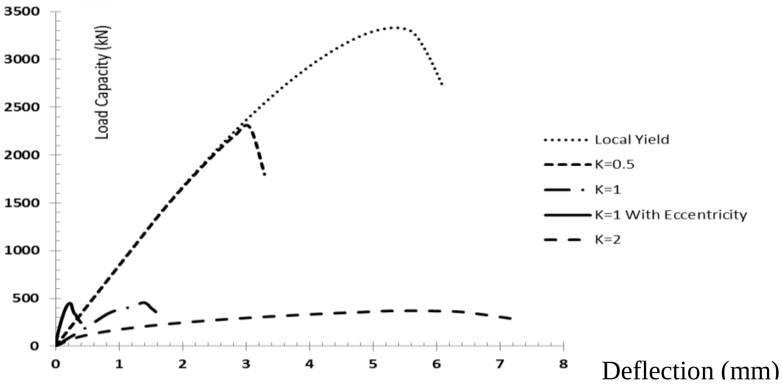


Fig. 10 The bearing capacity-displacement diagram for different effective column lengths at a loading strain rate of 23 mm/s

As can be seen in Fig. 10, higher bearing capacity is obtained for more engaged columns with less degrees of freedom in support conditions. Like as experimental result when the load applied without eccentricity the column failure occurs due to local yield (When the concrete materials in the middle of column reach the concrete yield point), not because of the reduced stability of the entire column. However, when eccentricity was applied in the middle of the column, the bearing capacity dropped from 3329 kN to 2292 kN.

5. The behavior of columns with FRP wrapped layers

To study the effects of carbon-fiber reinforced polymer (CFRP) layers on the strength of columns, two types of parametric analysis were performed on columns. The effects of the reinforcement sheet length wrapped along the column as well as the number of CFRP layers on the behavior and bearing capacity of the columns was investigated. It is assumed in all cases that the failure would not initiate from the adhesive confining strips attached to the column. In all cases, the loading strain rate was 23 mm/sec and both ends of the column ends were completely fixed. Table 3 shows the properties of CFRP sheets used in a limited run of the column according to Damian (2001).

Table 3 The characteristics of CFRP sheets

Thickness of sheet (mm)	Shear modulus (MPa)	Tensile strength (MPa)	Poisson's ratio	Modulus of elasticity (GPa)	Composite
1.27	G_{xy}=91.7 G_{yz}=16.7 G_{xz}=16.7	3790	ϑ_{xy}=0.2 ϑ_{xz}=0.2 ϑ_{yz}=0.2	E_x=220 E_y=40 E_z=40	CFRP

5.1 CFRP layers with a length of 2000 mm

To strengthen the columns, 2000 mm wrapping tape was applied over the length of the column, where it was expected that it would be able to confine the concrete in the middle of the column. Because of buckling failure accorded in column, capacity bearing not changed just the failure pattern was jumped to the end of warping layer. This type of failure happened because of warped layer helped column to transfer the stress along the length. The failure pattern showed in Fig. 11.

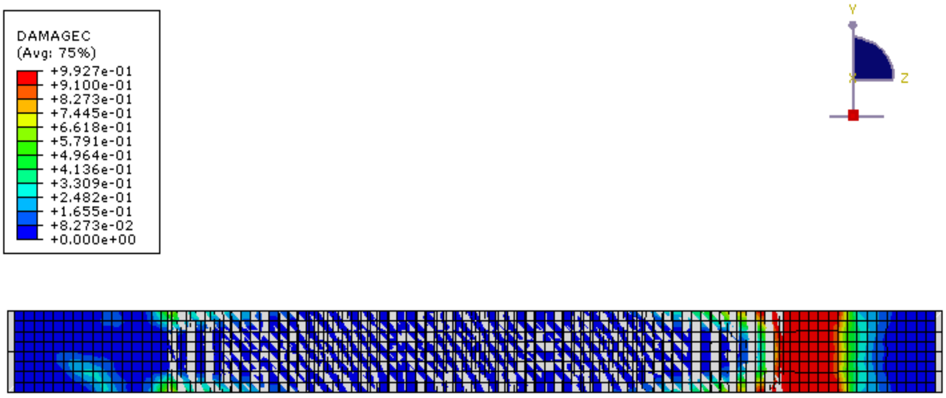


Fig. 11 Failure pattern for 2000 mm length of CFRP

5.2 CFRP layers with a length of 3000 mm

To strengthen the columns, full wrapping tape was applied over the entire length of the column, where it was expected that it would be able to bind the concrete in the middle of the column. Observations show that the stress distribution developed expected behavior for the column. The failure pattern of the wrapped column was as follows (to show the failure pattern, the reinforcing tape has been removed from the model).

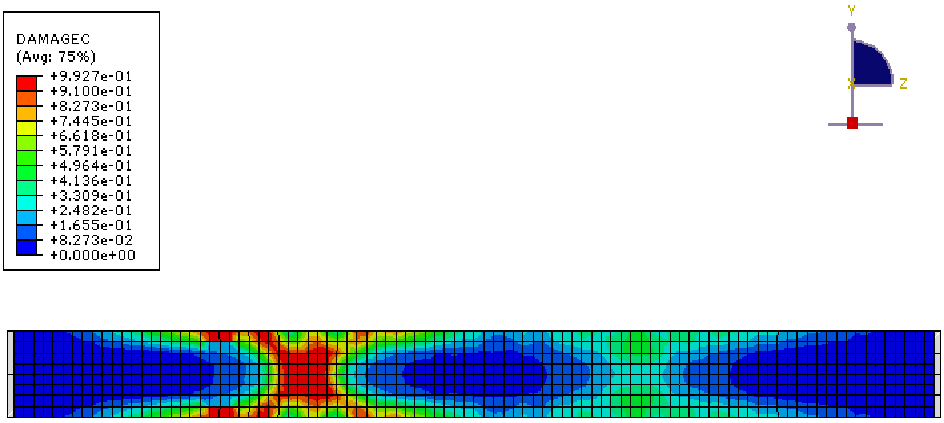


Fig. 12 The failure mode for a CFRP sheet with a length of 3000 mm

According to Fig. 12 the failure begins circa one-third middle of the column. Inevitably, with increasing the failure strain rate, the column will continue to damage from one side. Additionally Fig. 14 reveals the bearing capacity and strain having reached its ultimate capacity, where the increased strain is mainly due to the confinement of concrete between CFRP layers.

5.3 The effect of number of wrapped layers

To investigate the effect of number of CFRP layers on the bearing capacity and failure strain, 2, 3, 4, 5, 6, 7 and 8 layers were used to strengthen the columns. Fig. 14 shows the load-displacement diagram. As shown, increasing the number of layers up to 3 layers leads to a slight increase in the strength. However, the addition of 4 composite layers significantly increases the bearing capacity so that the column strength increased by 17.5%.

Table 4 Effect of CFRP layer numbers

Number of CFRP layers	Bearing capacity (kN)
Without CFRP	3329
2	3344
3	3403
4	3911
5	4335
6	4661
7	5021
8	5383

5.4 The optimal number of CFRP layers

To obtain the optimal number of wrapped CFRP layers, an investigation was performed into measuring the strength with each respective layer added. Fig. 13 shows the increase in strength

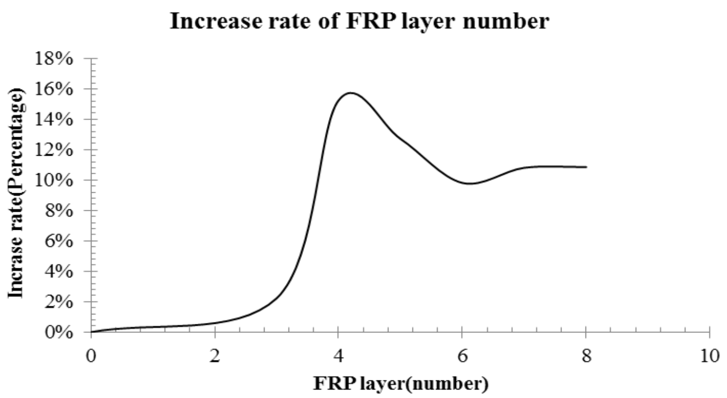


Fig. 13 The rate of capacity increase versus the number of FRP layers

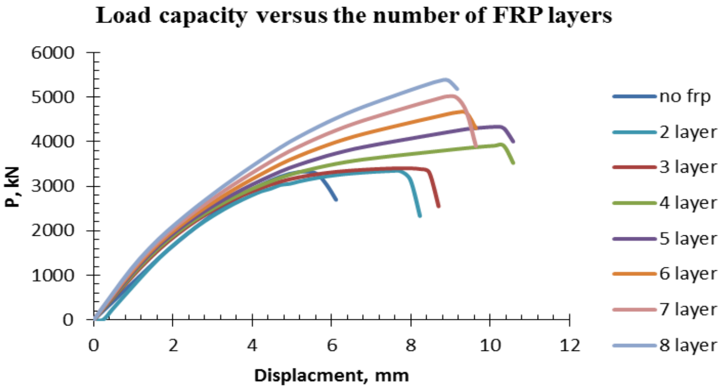


Fig. 14 The bearing capacity versus the number of FRP layers

Table 4 The numerical and experimental bearing capacities and strength enhancement factors

Loading type results	Quasi-static with φ factor (φ=0.9)	Quasi-static	23 mm/s	45 mm/s
Modeling load capacity (KN)	2964.6	3293.9	3329.7	3359.5
Experimental load capacity (KN) (Zheng and Xu 2012)	2941.0	3267.7	3304.0	3390. 0
DIF P(modeling)	1.00	1.00	1.12	1.13
DIFP (experimental) (Zheng and Xu 2012)	1.00	1.00	1.12	1.15
Deu (modeling)	5.24	5.24	5.39	5.40
Deu (experimental) (Zheng and Xu 2012)	5.70	5.70	6.50	6.80
DIF D (modeling)	1.00	1.00	1.02	1.03
DIF D (experimental) (Zheng and Xu 2012)	1.00	1.00	1.14	1.19

with increasing the number of layers. As can be seen, the use of four wrapped layers leads to maximum bearing capacity for the column, but any further layers added then decreases the bearing capacity sharply following by an average constant trend with a rate of 10% (as compared to previous layers). It must be noted that when only three layers (or less) are used, the column shows very limited strength rate where only the bearing capacity has increased. Overall, Fig. 13 demonstrates that only the minimal use of four CFRP reinforcement layers is the most effective means towards the strengthening rate. Furthermore, Fig. 14 reveals that with increasing the number layers of more than four layers, there is a decline in the strain capacity corresponding to the failure instant. Table 4 shown more information about numerical and experimental bearing capacities and strength enhancement factors.

Where: DIF P calculated from Force, DIF D calculated from deflection and Deu is amount of displacement at failure

6. Conclusions

This study has examined the performance and bearing capacity of reinforced concrete columns and influential factors demonstrating that the finite element is sensitive by element size on the column behavior and failure mode. The correct size of elements will have a significant impact on the behavior and failure pattern of concrete columns, where it is recommended that elements with the same size are used along all three axes. With increasing the loading strain rate, strain bearing capacity and the ultimate bearing capacity will increase. Degrees of freedom in support conditions of column plays important role in bearing capacity and with eccentricity in middle of column bearing capacity fell by 45% from 3329 kN to 2292 kN. The imperfect arrangement of the CFRP layers does not increase the bearing capacity of the columns under rapid loading, but it will affect the failure pattern of the column and also wrapping all the column with CFRP layers is a very effective. The results clearly show that the bearing capacity increases with increasing the loading strain rate of CFRP layers and the number of layers CFRP. Overall, this research has argued that the most economical plan to strengthen the concrete columns is to use a minimum of four CFRP layers which increases the bearing capacity by 17.4% and also increases the strain capacity by 50% through confining the concrete.

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