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Time-dependent Numerical Modeling of Plain Concrete Columns Wrapped by FRP Sheets

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ABSTRACT

The demand for strengthening structures becomes necessary when an increase in load is inevitable. For instance very little information is available on the time-dependent behaviour of strengthened concrete columns. Also, this is a primary factor hindering the widespread uses of FRP strengthening technologies in the construction implementations. This paper investigates the behaviour of strengthened concrete columns with FRP sheets subjected to long-term loading by non linear finite element analysis using ANSYS computer package. A three-dimensional finite element model has been used in this investigation. This study achieved a good agreement between numerical and experimental results, it was found that the percentage of error of specimens do not pass (5%) for creep strain. In addition, a parametric study was performed to study the effect of different factors on the behaviour of FRP strengthened concrete columns.

1. Introduction

Concrete structures strengthening started with the early use of concrete as a construction material. The demand for the strengthening of these structures became necessary when an increase in load was inevitable or when the structure's function is altered from its original purpose. Examples of the latter case are (i) residential buildings converted to storage and (ii) extra loads due to additional floors of an existing building [1].

Long-term behaviour of the structure depends mainly on the deformation properties of the concrete, in particular, creep and shrinkage. Several studies have investigated the effect of time on the reinforced concrete columns [2-5] while the long-term behaviour of concrete filled steel tube (CFT) investigated by [6-8] and they proposed analytical models in their studies. Refrence [9] studied the time-dependent behavior of circular concrete columns. Their study is based on two methods to strengthen columns: concrete-filled FRP tubes (CFFTs), and fibre warped concrete columns (FWCCs). As a result of their study, on time-dependent behaviour of concrete columns, [9] stated that the creep strain of FWCC is higher than CFFT and the effect of confinement on creep of the concrete core is not as significant as the effect of sealing the concrete and the stress redistribution that occurs between the concrete and the FRP. Refrence [1] investigated creep behaviour of confined and unconfined concrete columns in the shape of cylinders having dimensions of 150mm in diameter and 900mm in height. In his work, [1] used carbon fibre reinforced polymer (CFRP) material in strengthening. The result shows that confinement with FRP delay microcracking appearance and decrease creep strain. Refrence [10] investigated the behaviour of creep of square and circular concrete columns strengthened by aramid fibre reinforced polymer (AFRP) sheet (fully and partially), the dimension of columns were

(150*150*400) mm for the square column and (150*450) mm for circular columns. The result shows that there is no cross-sectional effect on the creep behaviour. Finaly, this section included reviewing the researches that investigated the long-term behaviour of reinforced concrete columns, confined concrete columns with steel and FRP strengthening concrete columns with all types, CFRP, GFRP and AFRP. However, a little studies deal with numerical investigation including time effects. This work deals with a theoretical investigation on viscoelastic material (concrete) with the time dependent behaviour of concrete columns strengthened with FRP. Finite element analysis is used in this study utilizing ANSYS package.

The purpose of this study is to simulate the strengthened plain columns with FRP sheets using nonlinear FEM, and the objective of the research program is making comparison between the experimental test results and numerical results obtained from the finite element analysis and determining the effect of the following parameters on the behaviour of strengthened column: type of FRP (Glass or Carbon), magnitude of sustained load and compressive strength.

2. Finite Element Modeling

2.1. Model Idealization

A twenty nodes quadratic isoparametric element called VISCO89 in ANSYS package having three degrees of freedom at each node (translations u, v and w in the nodal x, y and z directions respectively), as

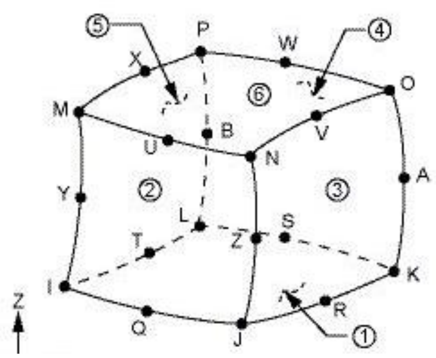


Figure 1. 20-nodes VISCO89 element [11].

shown in Fig1. This element has viscoelastic and stress stiffening capabilities. The FRP sheet is represented by shell element SHELL41 (four nodes quadratic-order membrane) as shown in Fig2., this element have membrane (in-plane) stiffness but no bending (out-of-plane) stiffness with three degrees of freedom u, v and w in x,y and z-direction respectively at each node.

2.2. Viscoelasticity in ANSYS package

There are many convenient models for viscoelastic materials that can fit the experimental data such as (Maxwell model, Kelvin model and Prony series). Prony series model are used in this study for representing the viscoelastic constitutive concrete model. Creep and relaxation tests are usually tested in the time range. In creep test, a constant stress σ is applied and the strain is to be measured, the ratio between the measured strain and stress applied is the compliance D(t)=ε(t)/σ. In the relaxation t is measu n the measured stress and strain applied is the relaxation E(t)=σ(t)/ε.

Figure 2. 4-nodes SHELL41 element [11].

Prony Series:

When the time domain became long, the refined new model becomes necessary, such as Prony series that consist of n number of decaying exponentials [12].

$$\boldsymbol{E(t) = E_\infty + \sum_{i=1}^{n} E_i \exp(-t/\tau_i)} \quad (1)$$

where $\boldsymbol{E_\infty}$ is the equilibrium modulus, $\boldsymbol{E_i}$'s are the relaxation moduli and $\boldsymbol{\tau_i}$'s are the relaxation times.

If the material is a liquid ($\boldsymbol{E_\infty = 0}$). The larger the $\boldsymbol{\tau_i}$ the slower the decay is. At $\boldsymbol{t = 0}$, note that $\boldsymbol{E_0 = E_\infty + \sum E_i}$, equation (1) can be written as follows

$$\boldsymbol{E(t) = E_\infty + \sum_{1}^{n} m_i E_0 \exp(-t/\tau_i)} \quad (2)$$

Figure 1. 20-nodes VISCO89 element [11].

where $\boldsymbol{m_i = E_i/E_0}$ are the dimensionless moduli.

Prony Series can be expressed using a shear modulus (G) and bulk modulus (K), G and K are calculated from the American concrete institute (ACI-318) [13] equations where,

$$\boldsymbol{G(t) = G_\infty + \sum_1^n g_i G_0 \exp(-t/\tau_i)}$$

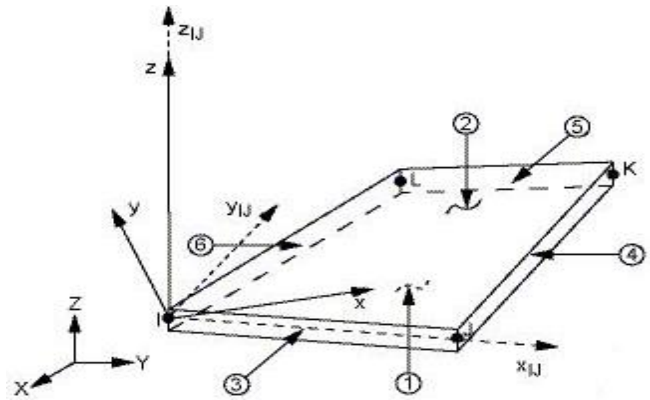
$$\boldsymbol{K(t) = K_\infty + \sum_1^n k_i K_0 \exp(-t/\tau_i)} \quad (3)$$

where $\boldsymbol{G_0, K_0}$ refer to initial shear modulus and bulk modulus, respectively; $\boldsymbol{g_i = G_i/G_0}$ and $\boldsymbol{k_i = K_i/K_0}$the dimensionaless shear and bulk moduli and $\boldsymbol{G_i, K_i}$ represent shear and bulk modulus of the i-th term. When $\boldsymbol{t = 0}$, $\boldsymbol{G_\infty = G_0(1 - \sum_1^n g_i)}$, $\boldsymbol{K_\infty = K_0(1 - \sum_1^n k_i)}$, the Prony series can be written as

$$\boldsymbol{G(t) = G_0(1 - \sum_1^n g_i) + \sum_1^n g_i G_0 \exp(-t/\tau_i)}$$

$$\boldsymbol{K(t) = K_0(1 - \sum_1^n k_i) + \sum_1^n k_i K_0 \exp(-t/\tau_i)} \quad (4)$$

The experimental results are represented by a mathematical function. On one hand, the Prony series used a mathematical curve to represent viscoelastic materials in the present study. On the other hand, the procedure to obtain Prony series from experimental data (curve fitting procedure) is not easy, involving many numerical tasks. For this reason, a computer program written in Fortran power station 4.0 is developed to perform curve fitting



of Prony series, this program depends on the least squares method to obtain the coefficient of Prony series.

3. Verification by Numerical Examples

Two strengthening concrete columns were analyzed in this paper, one of these columns is strengthened with glass fibre reinforcement polymers (GFRP) sheet which is investigated by [8] and designed as FWCC, while the other column is strengthened with CFRP sheet which is investigated by [1] and designed as B1C1.

The first column (FWCC) have a dimension of 305mm height and 152mm diameter while the second column (B1C1) is 900mm height and 150mm diameter. The dimensions and some properties of these columns are illustrated in Table (1) and the description of columns is given in Fig3. and Fig4.

Table 1. Material Properties of FWCC and B1C1 Concrete Columns[1,9].

Colum	Dimensions	Compressive (f'_c) (MPa)	Tensile strength (f_t) (MPa)	Type of FRP	Age at loading s)
FWC		29	3.34		
B1C		39	3.87		)

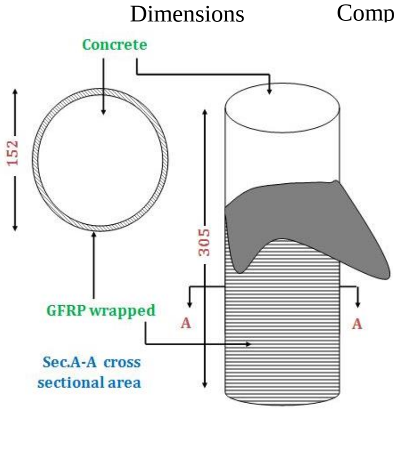


Figure 3. Details of FWCC concrete column [9].

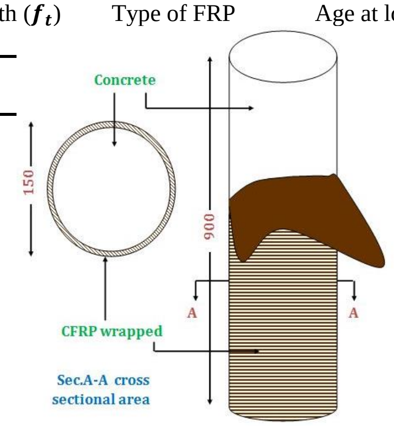


Figure 4. Details of B1C1 concrete column [1].

3.1. Finite Element Idealization and Material Properties For (FWCC) and (B1C1) Models

The columns were simulated by using (VISCO89) and (SHELL41) elements to model concrete and FRP, respectively. (FWCC) model consists of (2352) elements while (B1C1) consist of (7056) elements. Table (2) illustrates material properties that used to simulate these models in FEM.

At a lower plane (z=0) for (FWCC) and (B1C1) models all nodes were restrained in all direction, the eight nodes in coordinate (0,76,266.9), (0,76,279.6), (0,76,292.3), (0,76,305), (0,-76,266.9),(0,-76,279.6),(0,-76,292.3),(0,-76,305) for (FWCC) model were restrained in x and z direction, while the sustained load (173.5kN) was applied at age=21 day on the all nodes in an upper plane (z=305), but in the (B1C1) model two nodes in coordinate (75, 0,900), (-75, 0,900) were restrained in x direction and the sustained load with value equal to 605KN applied at age=360day on the all nodes at the upper plane (z=900). The finite element model of (FWCC) and (B1C1) columns given in Fig5. and Fig6.

Table 2. Element type and material properties for (FWCC) and (B1C1) models [1,9].

Concrete (VISCO89)							
Column	Cross section	□′□ (MPa)	□□* (MPa)	□□* (MPa)	□□* (MPa)	v_u	v**
FWCC	Circle	29	25472	10613	14151	0.92	0.2
B1C1	Circle	39	29539	12308	16411	2.34	0.2
FRP (SHELL41)							
Column	Type of FRP	Thick. (mm)	□ (MPa)	□ (MPa)	□□ (MPa)	□□	v
FWCC	GFRP	1	□□=21000 □□=7000 □□=7000	□□□=1520 □□□=2650 □□□=1520	600	0.0283	v_{xy}=0.26 v_{yz} =0.30 v_{xz}=0.26
B1C1	CFRP	1	□□=62000 □□=4800 □□=4800	□□□=3270 □□□=1860 □□□=3270	760	0.012	v_{xy}=0.22 v_{yz} =0.30 v_{xz}=0.22

*According to ACI-318 equations [13].
**Assumed.
-Other information in table of FWCC from [9] and B1C1 from [1].

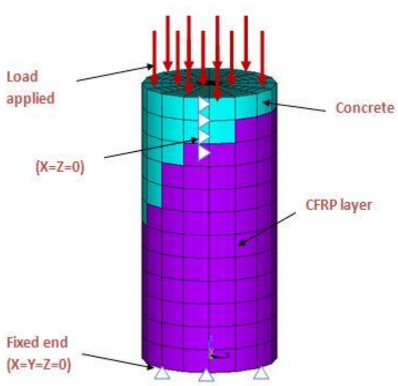


Figure 5. Finite element model for FWCC concrete column.

Figure 6. Finite element model for B1C1 concrete column.

3.2. Results of Analysis of FWCC and B1C1 Columns

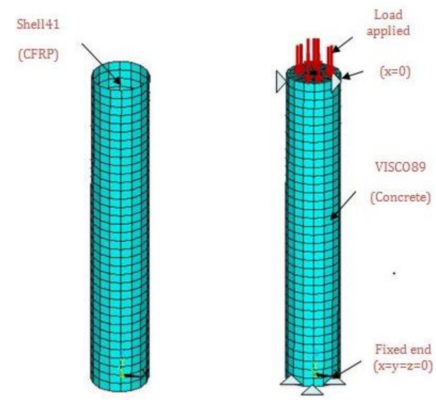
The analysis of creep for columns under sustained loading needs a function of shear modulus

relaxation which is obtained from Prony series fitting program that is written in Visual FORTRAN 5.0, these functions are given in Eq.(5) and Eq.(6) for FWCC and B1C1 columns, respectively.

ANSYS program requires the input of material characteristics, e.g., initial and final shear modulus, a number of Maxwell elements with relaxation modulus and discrete relaxation spectrum for each Maxwell element assuming the constant temperature and stress behaviour along age of structure indicated by the bulk modulus. From fitting the compliance function from ACI-209 model [14] and from equations of shear and bulk modulus .

By using Prony Series Fitting Program (PSFP) for Prony series representation of reduction in shear modulus, which is coded in FORTRAN power station 4.0 language, to obtain shear relaxation functions [15] .

These functions should be compared with ACI committee 209R creep model [14], according to this comparison the results give a good agreement with ACI model. The error of these functions does not pass (±1.5%) for concrete columns. The comparison of functions, the percentage of error, experimental and

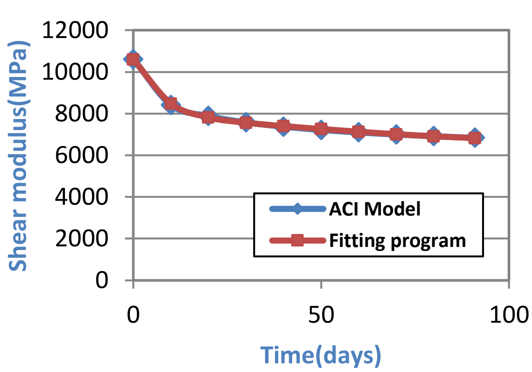


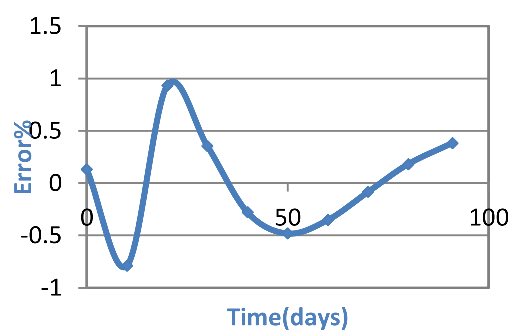
numerical curves, a variation of displacement, strain and principle stresses of concrete columns were shown in Fig7. to Fig18. While Table (3) shows the results of the experimental and finite element analysis of these columns.

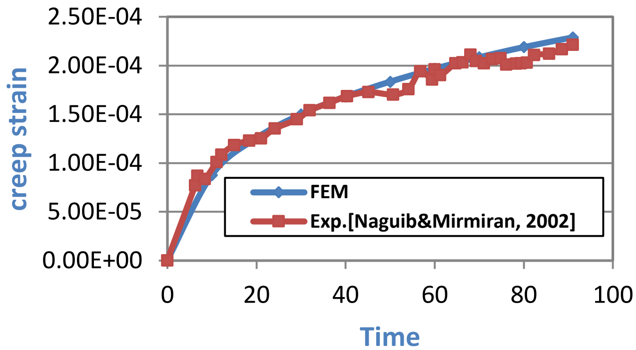
$$\boldsymbol{G(t) = 6549.14 + 5664.833exp^{(-t/10)} - 9093.15exp^{(-t/20)} + 7478.688exp^{(-t/30)}} \quad (5)$$

$$\boldsymbol{G(t) = \square\square\square\square.\square\square\square + \square\square\square\square\square.\square\square exp^{(-t/\square\square)} - \square\square\square\square\square.\square exp^{(-t/\square\square)} + \square\square\square\square\square.\square\square exp^{(-t/\square\square)}} \quad (6)$$

By comparing the results of experimental and finite element method of time-creep strain curves, a good agreement between finite element and experimental results can be seen.







Time-Creep
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Figure 10. Shear Modulus Relaxation vs Time for (B1C1) Column.

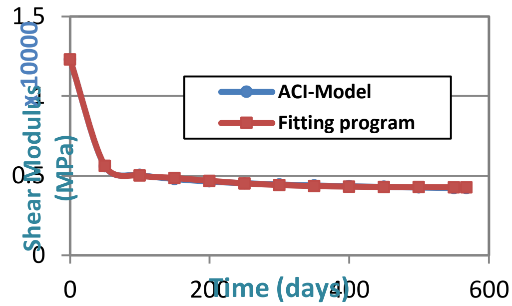
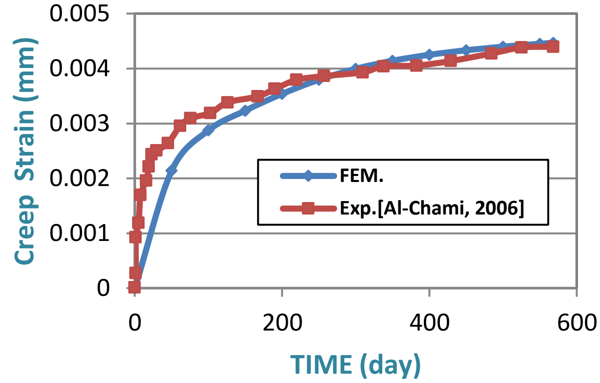
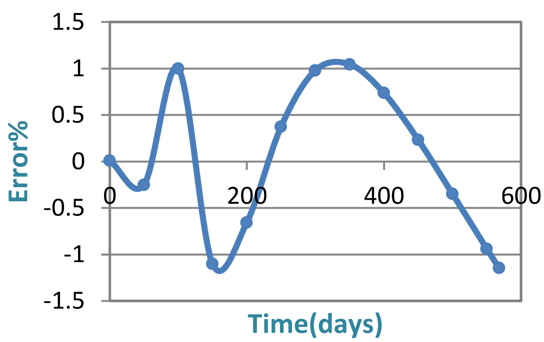


Figure 8. Percent of Error vs Time for (FWCC) Column.





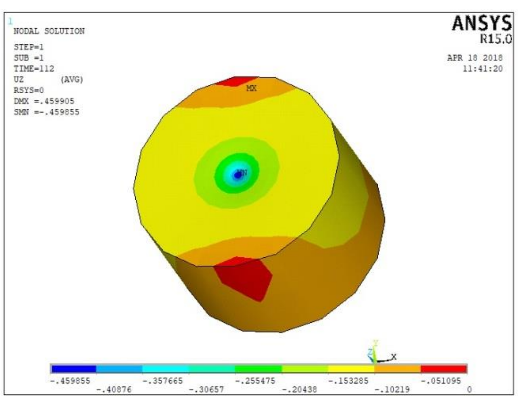


Figure 13. Displacements in z-direction of cross section for FWCC model at 91day.

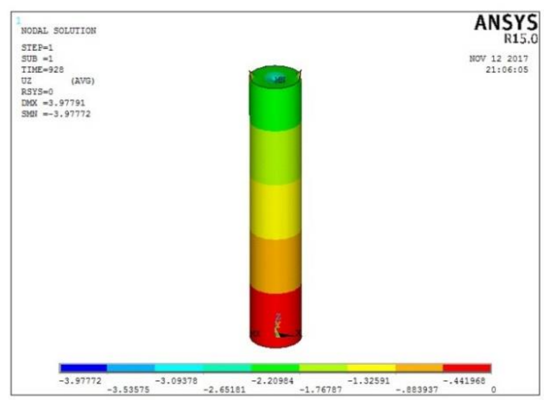


Figure 14. Displacements in z-direction of cross section for B1C1 model at 568day.

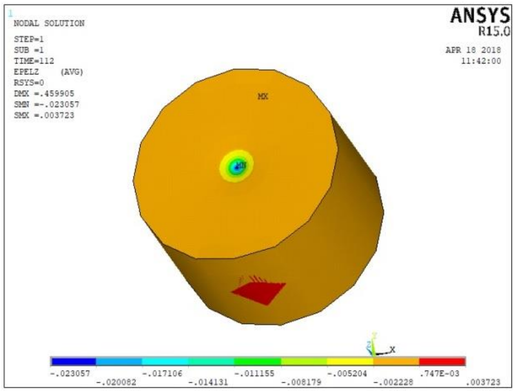


Figure 15. Strains in z-direction of cross section for FWCC model at 91day.

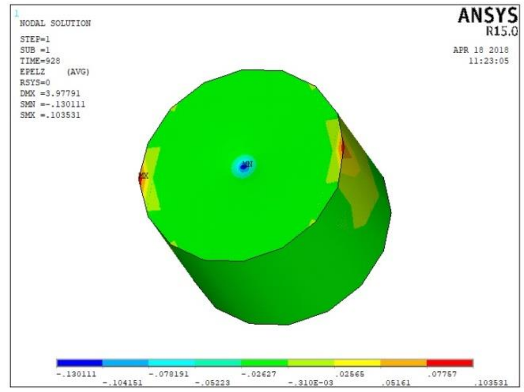
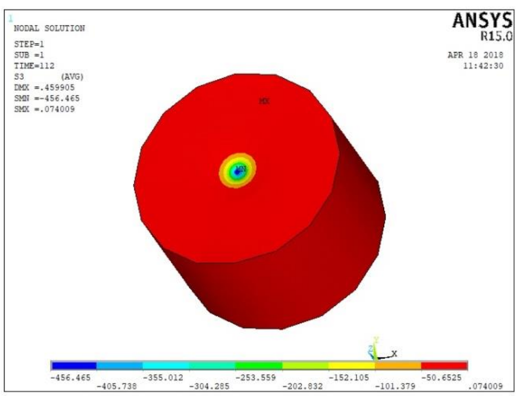
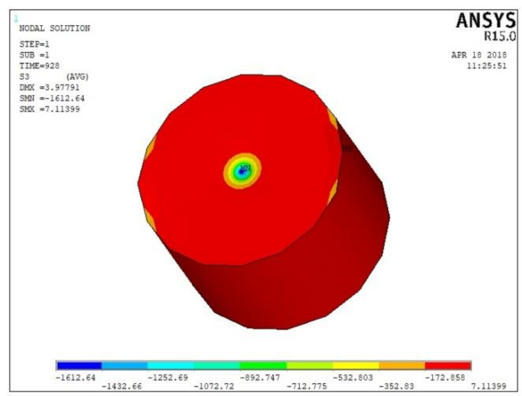


Figure 16. Strains in z-direction of cross section for B1C1 model at 568day.





rection of cross
91day.

Figure 18. Principal stresses in z-direction of cross section for B1C1 model at 568day.

Table 3. The results of experimental and finite element method of (FWCC) and (B1C1) models

Column	Creep strain (Exp.)	Creep strain (FEM)	$\frac{\textbf{Creep strain(FEM)}}{\textbf{Creep strain(Exp.)}}$	Percentage of increase%
FWCC	0.0002213	0.000229	1.0348	3.48
B1C1	0.0044	0.0045	1.0227	2.27

4. Paramitric Study

In this paper, a parametric study was performed to study the effect of some parameters on the strengthened concrete columns is studied such as the magnitude of the sustained load, compressive strength, and FRP type. The short name of the model consists of three symbols where

FRP Type (Glass or Carbon). Load Applied (200, 800, 2000)kN.Compressive Strength (30, 40, 50)MPa and the symbols (FT, L and C) in figures refers to variable FRP type, load and compressive strength respectively.

4.1. Magnitude of Sustained Load Effect

The magnitude of sustained load is a major parameter which affects the creep, three values of sustained load are made in this study to evaluate the strengthened concrete columns behaviour under dif-

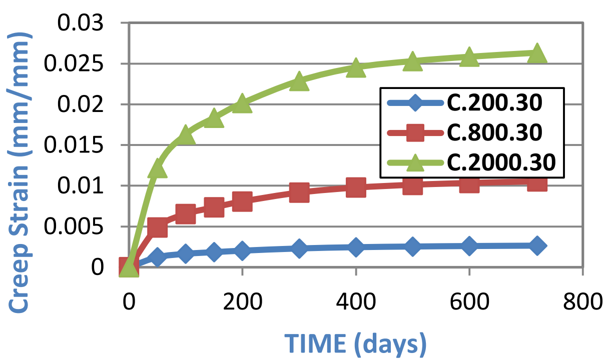


Figure 19. Time vs Creep Strain of Models (C,L,30)

ferent level of load with the same compressive strength and same dimensions, (200,800 and 2000)kN are taken. From Fig.19 to Fig.24. the results show that by increasing load for the samples, the creep strain is increased with the same dimension and same compressive strength. Increading the sustained load from (200 to 800)kN and (800 to 2000)kN cause an increase in creep strain about (3 and 1.5) times, respectively. According to [16,17] the stress applied by 40% of compression strength leads to the fact that the relationship between creep and stress is linear while increasing the stress by more than 40% of the compression strength, the relationship is nonlinear due to the micro-crack where the micro-crack increases the value of creep strain. Gen-

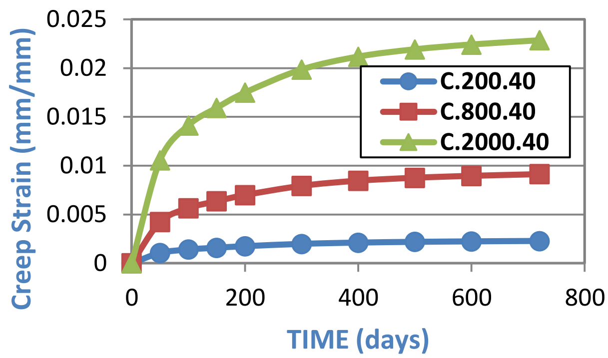


Figure 20. Time vs Creep Strain of Models (C,L,40)

erally, increasing the applied load leads to reducing the strength of the strengthened column under long-term where it increases creep strain.

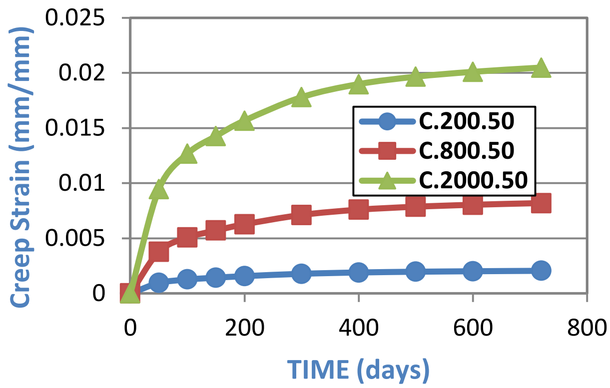


Figure 21. Time vs Creep Strain of Models (C,L,50)

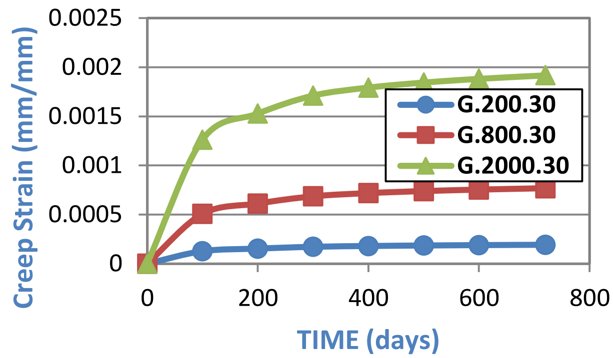


Figure 22. Time vs Creep Strain of Models (G,L,30)

4.2. Compressive Strength Effect

To study the effect of compressive strength on the behaviour of strengthened concrete column, three types of compressive strength (30, 40 and 50) MPa are selected. Generally it is observed that increasing the compressive strength lead to decrease in the creep strain. However, increasing compressive strength from (30 to 40)MPa and (40 to 50)MPa lead to decrease creep strain by 13.2% and 10.4%, respectively. Fig25. through Fig27. show the effect of compressive strength for (B1C1) column while Figs28. through Fig30. show the effect of compressive strength for (FWCC). Generally, the increase of compressive strength lead to enhance the behaviour of the strengthened concrete column under long term loading, which leads to decreasing the creep strain. The reason for the inverse relationship between concrete compressive strength and creep is that the low aggregate content in low concrete compressive strength as it is the aggregate that restricts creep therefore the creep value is low in high strength concrete.

Figure 23. Time vs Creep Strain of Models (G,L,40)

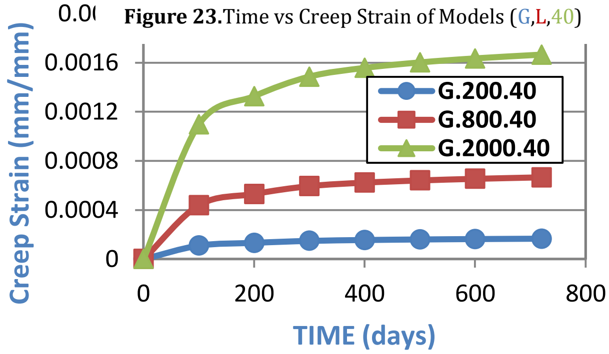


Figure 24. Time vs Creep Strain of Models (G,L,50)

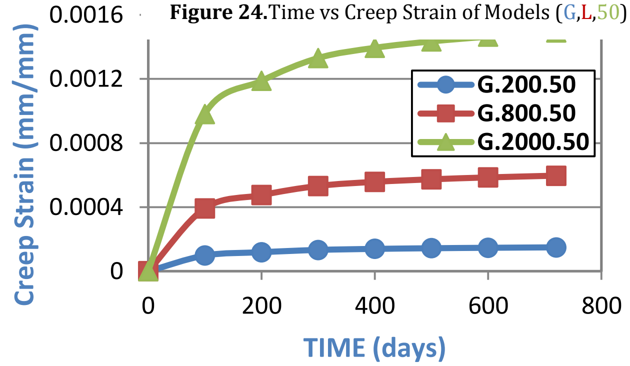
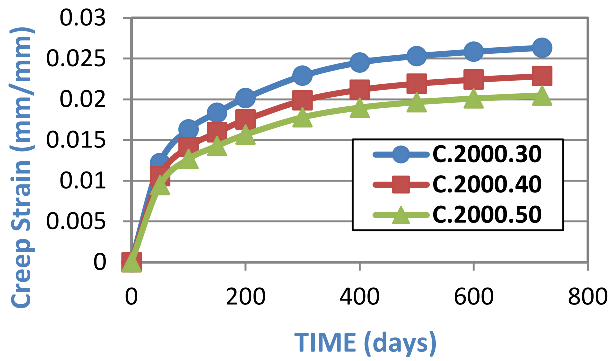
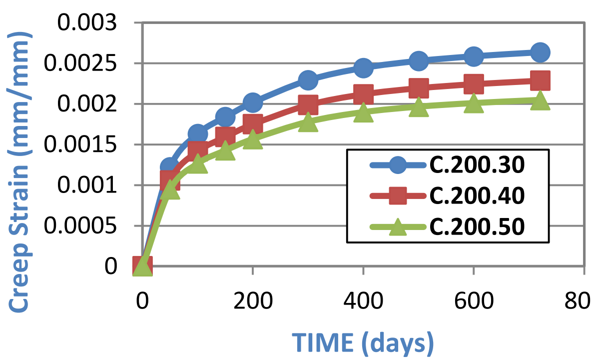


Figure 27. Time vs Creep Strain of Models (C,2000,C)



two columns.



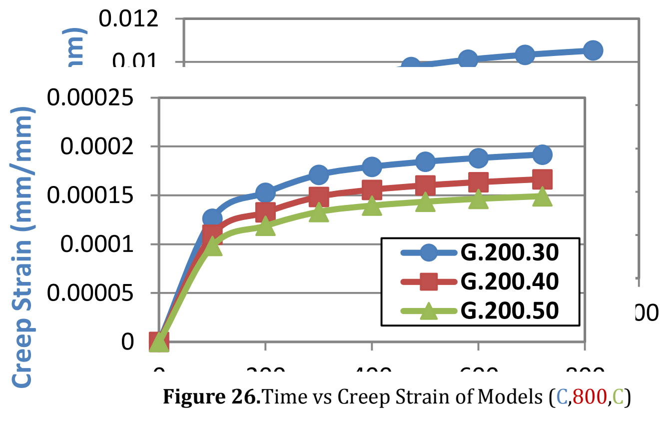


Figure 25. Time vs Creep Strain of Models (C,200,C)

Figure 26. Time vs Creep Strain of Models (C,800,C)

Figure 27. Time vs Creep Strain of Models (C,2000,C)

Figure 28. Time vs Creep Strain of Models (G,200,C)

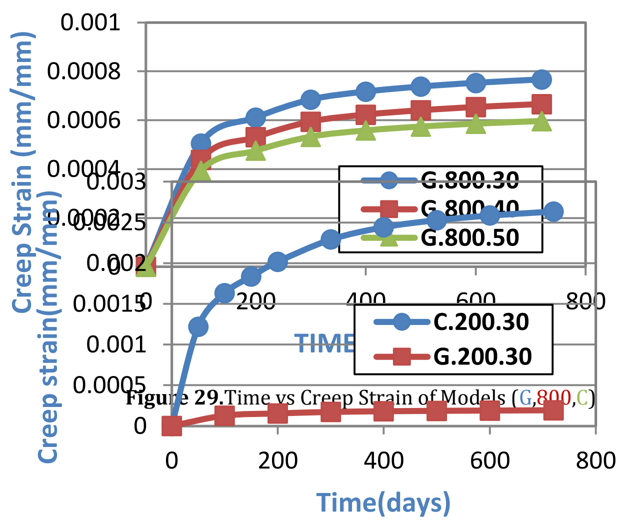


Figure 29. Time vs Creep Strain of Models (G,800,C)

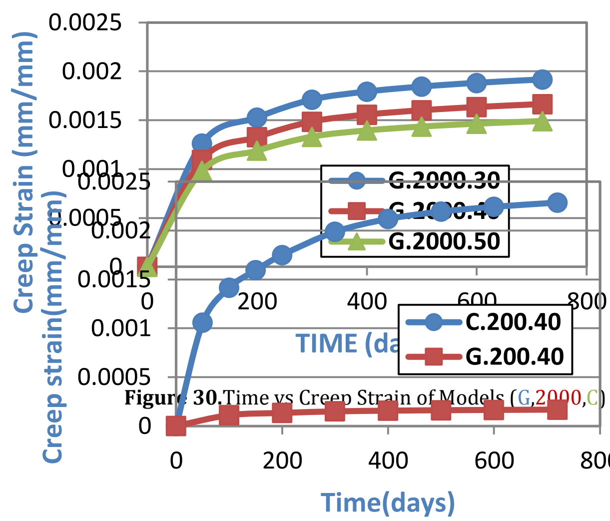


Figure 30. Time vs Creep Strain of Models (G,2000,C)

4.3. FRP Full Strengthening Type Effect

To study the effect of FRP type on the behaviour of strengthened concrete columns B1C1 column, which is strengthened with CFRP is compared with FWCC column which is strengthened by GFRP. Generally, it was observed that creep strain of B1C1 column is higher than FWCC column by 13 times, this is because the modulus of elasticity of CFRP is higher than that of GFRP [18]. Fig31. to Fig39. shows the comparison of these two columns.

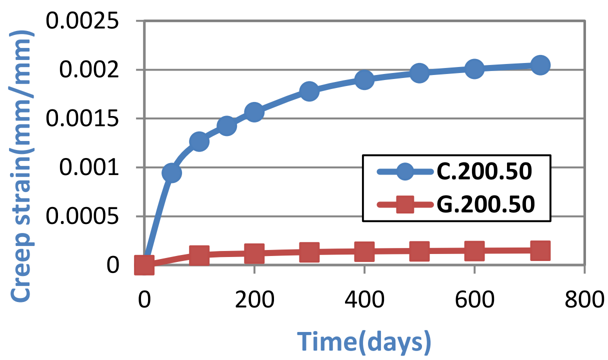


Figure 33. Time vs Creep Strain of Models (FT,200,50)

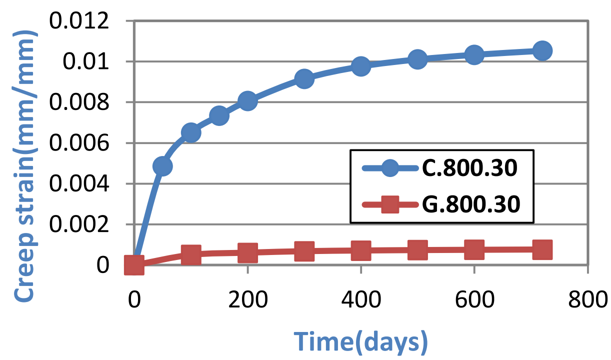


Figure 34. Time vs Creep Strain of Models (FT,800,30)

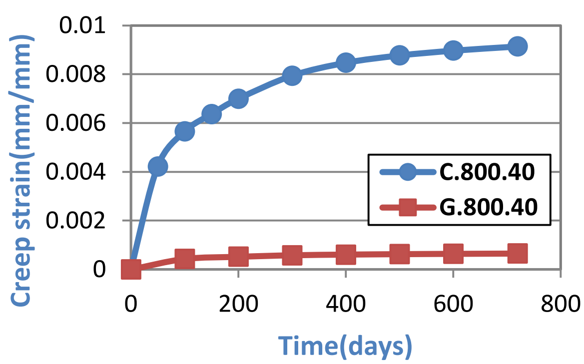


Figure 35. Time vs Creep Strain of Models (FT,800,40)

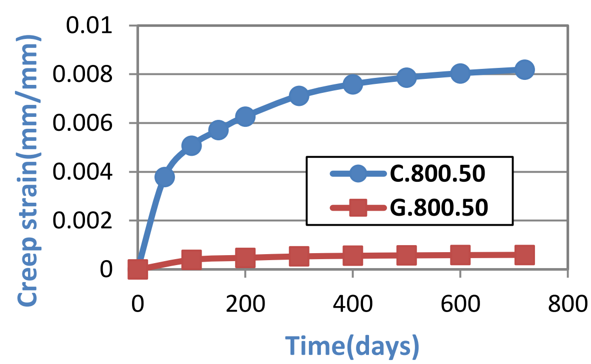


Figure 36. Time vs Creep Strain of Models (FT,800,50)

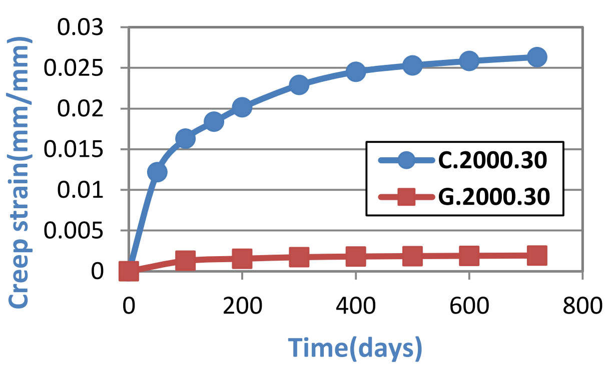


Figure 37. Time vs Creep Strain of Models (FT,2000,30)

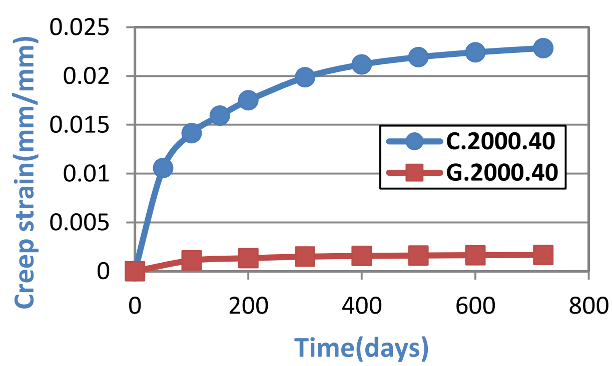


Figure 38. Time vs Creep Strain of Models (FT,2000,40)

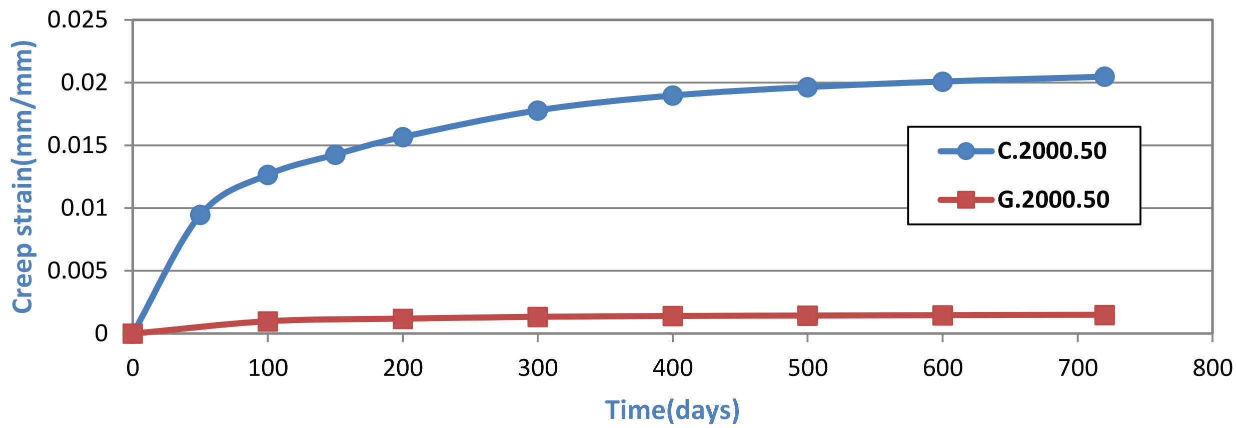


Figure 39. Time vs Creep Strain of Models (FT,2000,50)

5.Conclusion

1- Nonlinear finite element with viscoelastic model showed a good agreement when it was compared with experimental results, the maximum difference was 5.9%.

2- The finite element analysis results show a significant increase in creep strain of the FRP-wrapped reinforced concrete columns as compared with the unstrengthened columns about 167.9% and 86.4% for CFRP and GFRP respectively, because of the high tensile strain capacity of the FRP tubes in the hoop direction which increases the axial strain capacity of the confined columns.

3- Increasing of the sustained axial load capacity of the columns are significantly affected by creep strain behaviour. It was shown that when increasing the sustained load to 300% of the reference load, this leads to increase the creep strain about 300% for the same column specimen. That occurred because the residual stresses of concrete have been increased in the same manner.

4- the Increased magnitude of compressive strength with keeping the other factors constant leads to enhance the strength of strengthened concrete columns. Creep strain of concrete columns decreased about 13.2% and 10.4% when the compressive strength is increased from (30 to 40)MPa and (40 to 50)MPa respectively.

5- The ACI-209 model has good criteria for calculating the creep of the FRP confined concrete column. The difference between the ACI 209 model and test results of the of the FRP specimens is not significant. The max error of shear modulus it is founded to be less than 1.5%.

Nomenclature

$\mathbf{v}_{xy}$	Major Poisson's Ratio
$\mathbf{v}_{yz}$, $\mathbf{v}_{xz}$	Minor Poisson's Ratio
E_c	Elastic Modulus of concrete (MPa)
E_x	Elastic Modulus in x-direction (MPa)
E_y	Elastic Modulus in y-direction (MPa)
E_z	Elastic Modulus in z-direction (MPa)
G_{xy}	Shear Modulus in the xy Plane (MPa)
G_{xz}	Shear Modulus in the xz Plane (MPa)
G_{yz}	Shear Modulus in the yz Plane (MPa)
v_u	Ultimate creep coefficient

E_0	Initial modulus (MPa)	v	Poisson's Ratio
f'_c	Compressive strength (MPa)	τ	Loading age (day)
$f't$	Splitting tensile strength (MPa)	D	Inverse of elastic modulus
G	Shear Modulus (MPa)	$J(t,t')$	Creep function
K	Bulk Modulus (MPa)	η	Newton viscosity
t	Current age (day)	σ_0	Constant stress (MPa)

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