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Effect of Viscosity Parameter on Numerical Simulation of Fire Damaged Concrete Columns

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Abstract

The assessment of the residual strength of post-heated concrete structural members in a professional way is a prime factor to take a decision about the restoration or destruction of fire-damaged structure. This Paper explores the numerical modelling of RC square columns damaged by exposure to heat at 5000C, unjacketed. Software ABAQUS was used for numerical modelling of fire damaged compression member i-e column. The main objective of this study is prediction of axial load and axial deformation of fire damaged concrete using finite element studies. Moreover, a parametric nonlinear finite element (FE) research is carried out to check the effect of viscosity parameters on numerical simulation of fire damaged concrete columns. For the said objectives, numerical simulation of existing experimental study of fire damaged RC columns is conducted with varied values of viscosity parameters. The numerical analysis (Finite Element Modeling) indicated that axial load capacity decreases and axial deformation increases after exposure to fire. The experimental and numerical studies are compared in terms of load displacement analysis. The use of optimum viscosity parameter and its definition to FEM improves significantly the performance of convergence and reduces analysis time of numerical simulations of RC square columns. Moreover, a good agreement was found between the experimental and the finite model results.

Keywords: Fire Damaged; Viscosity Parameter; Concrete Damage Plasticity; ABAQUS; Numerical Modelling.

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1. Introduction

The international association of fire and rescue services report published in 2018 showed that more than 3 million fire incidents occurred around the world resulting about 18000 civilian deaths,58.6 thousands civilian injuries and million dollars directly property damage. With such high figure, it is inevitable to develop a procedure to assess the residual performance of structural system after fire [1]. Reduction in performance of building material is noted after exposure to high temperatures [2]. The exposure of building to fire resulted in 58% reduction in strength [3]. The use of Finite element model (FEM) for prediction of axial capacities and deformations is also employed these days. Mohamed Bikhiet et al. (2014) used it to check the behavior of fire damaged columns. He concluded that due to increase in surface temperature faster failure occurred. Moreover, Ma et al. (2012) used it for numerical simulation of already performed experimental work. The concrete damage plasticity model was adopted for the calculation of constitutive concrete material used in the columns and the viscosity coefficient was discussed. It was specified that until finding a reasonable value for viscosity parameter, a parametric study should be conducted in order to improve convergence of numerical simulation. Two different constitutive material models are offered in ABAQUS/Standard, which is an implicit analysis program, for the analysis of concrete at low confining pressures: the smeared crack concrete model and the concrete damaged plasticity (CDP) model. Moreover, the CDP model is based on the degradation of the elastic stiffness induced by plastic straining both in compression and tension (assumption of isotropic damage) [4]. A non-linear FEM has been

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adapted by Rami H. for shear deficient heat-damaged concrete**.** He concluded that, for CDP material model it can be defined flow potential, yield surface, and viscosity parameters [5]. The numerical model developed for retrofitting of damaged structural member showed that the developed model can be an effective tool to predict the performance of retrofitted beams under dynamic loading condition [6].

Piscesa et al. (2017) got excellent results in his study where the steel rebar is modelled as a truss element with elastic-perfectly plastic material behaviour. The concrete is modelled as 8-noded hexahedral element [7]. Accuracy and reliability are verified by simulating experiment on a plain concrete specimen. Two laboratory experiments consisting in pushing until failure two 2-D RC frames are simulated with the proposed approach to investigate its ability to reproduce actual monotonic behaviour of RC structures [8]. FE numerical simulation has been employed by many researchers to predict the behaviour of heat damaged RC columns with different wrapping materials and bonding dimensions [9-11]. Mohamed Bikhiet et al. (2014) checked the nonlinear behaviour of damaged concrete. He found that along with the application of load and increase in surface temperature the column failed faster. The simulation also showed the effect of temperature on stress and its distribution [12, 13]. ABAQUS is actually implicit analysis program which constitutive model. Two main models used in ABAQUS for modelling concrete are “Brittle Cracking Model for Concrete” and “Concrete damage Plasticity model” [14]. The concrete damaged plasticity model is most widely used model based on the assumptions of isotropic damage and degradation of elastic stiffness induced by plastic strain [15-20].

It has been observed from the literature that the finite element behavior of the Post heated unconfined concrete columns using software (ABAQUS) is less explored. There is a gap in literature about effect of viscosity parameter on numerical simulation of fire damaged RC Columns. An effort is made in this research to give a model for prediction of axial load and axial deformation of fire damaged RC Square Column and effect of viscosity parameter on numerical simulation. Therefore, to accurately analyze and stimulate such columns critical parameters that influence the axial capacity of RC columns needs to be studied.

1.1. General Analysis

Abaqus (FEM code) which is general purpose code was used for nonlinear analysis. The library of Abaqus contains several constitutive models and has a complete geometric modeling capability. Analysis follows several steps, each of which shows response simulation. This system also includes preprocessing and post processing techniques. FEM code can cope with coupled analysis, meaning temperature and displacements are integrated simultaneously.

2. Material Properties

2.1. Damaged Plasticity Model of Concrete

The plastic behavior of concrete can be defined by any of the following constitutive three models in ABAQUS, the concrete Smeared Cracking model (CSCM), Brittle Cracking Concrete (BCC) and Concrete Damaged Plasticity model (CDPM).The damaged plasticity model compacts with compressive, plastic, and tensile behavior and damaged mechanism of concrete. ABAQUS by default defines compressive, tensile and plastic behavior of concrete.

2.2. Viscosity Parameter (μ)

This is parameter that is used to prevent numerical instabilities and strain localization. The behavior of structural members that is column and beam actually define the behavior of whole structure. That is why nonlinear behavior of these members is very important for safe design of structures. Plastic, compressive and tensile behavior of concrete are the main inputs required in Plasticity model. This model (CPD) can be regularized using viscoplasticity by allowing stresses to be outside yield surface. Duvaut-Lions generalization is used, which states Viscoplastic strain rate tensor, ε_{v}^{pl} as:

$$\varepsilon_{v}^{pl} = \left(\varepsilon^{pl} - \varepsilon_{v}^{pl}\right)/\mu \qquad (1)$$

Here μ is viscosity parameter and ε^{pl} is plastic strain. Small values of viscosity parameters are used to achieve good results. The general guideline given by Lee et al. (1998) is that it is taken as 15 % of time increment [4, 21].

2.3. Damage Parameters

The ratio of cracking strain to the total strain is known as tensile damage parameter (dt). Similarly the ratio of inelastic strain to the total strain is compressive damage parameter (dc). If these parameters are not specified, the model is termed as plasticity model.

2.4. Dilation Angle

This is an angle of cracking of concrete. The value of dilatancy parameter αp ranges from 0.2 to 0. 3 [22, 23]. For specified range the dilation angle should be between 310 to 420. In this study dilation angle ranging from 30^0 to 45^0 were examined.

3. Experimental Study

An Experimental study conducted by Yaqub et al. (2010) is selected as reference study in order to create a numerical model of RC square Columns [24]. The specimen that is post heated non-jacketed (S3) is used as reference verification specimen. The detailed geometry, reinforcement is displayed in Figure 1. The load vs. deformation relationship developed experimentally that is used as reference is shown in Figure 2.

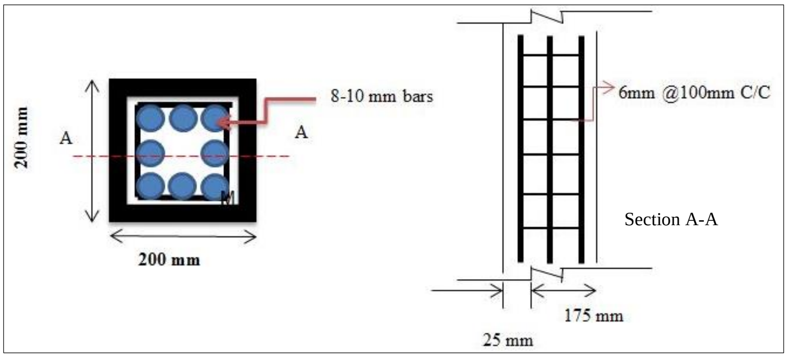


Figure 1. Reinforcement arrangement in square column

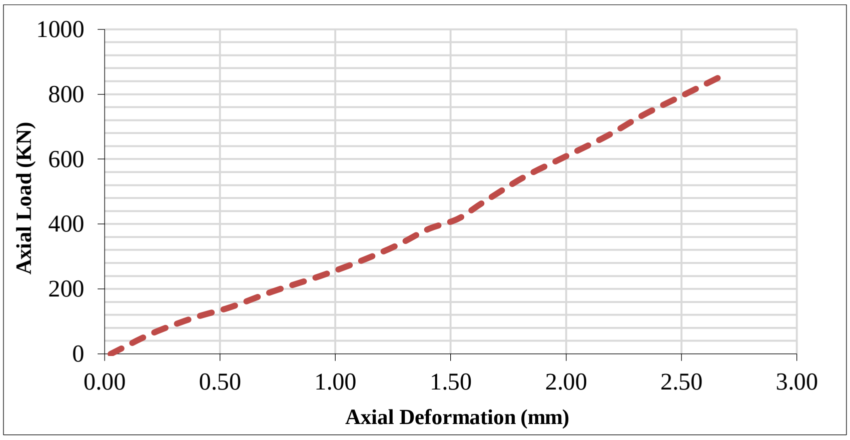


Figure 2. Axial strain of post heated/non-jacketed columns [24]

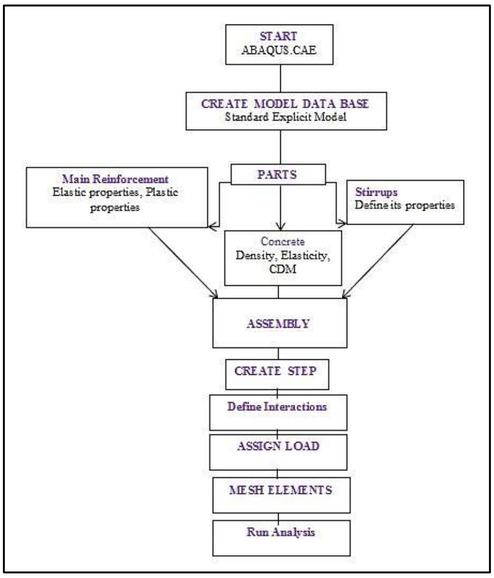


Figure 3. Steps followed during Simulation of heat damaged RC Square Columns

4. Numerical Modeling

Finite element models (FEM) for Post heated unconfined RC Square column has been evolved by the usage of ABAQUS as shown in Figure 4 .Concrete is defined as C3D8R which means eight noded brick element with reduced integration. Due to reduced integration, the locking phenomena observed in C3D8 element don't show. Stress, strains are most accurate in the integration points. The integration of C3D8R element is located in the middle of element. Longitudinal and Transverse steel is defined as T3D2, two-noded 3D truss elements. Top of the concrete column takes load from steel plate so interactions defined are bottom of steel plate is declared as master surface and top of concrete column is defined as slave surface. However, these interactions are opposite at bottom of column because in that case bottom of column transfer force to steel plate .Steel is embedded in concrete.

The form of element selected and the interactions among numerous parts assembled is given in Table 1. The interaction of steel with concrete that limits the nodes of steel bars components to the compatible levels of freedom of the host neighborhood elements (concrete) is defined through embedded region constraint given in ABAQUS general. Static monotonic loading was implemented on the pinnacle with the assistance of displacement manage technique to work out the axial load-deflection records of concrete columns up to failure. A precipitated displacement of 25mm became implemented as uniformly distributed load on pinnacle of concentric columns." Tie constraint" is used for steel plates that are actually placed at the top and bottom of column.

The parameters required to define the plasticity model of concrete are dilation angle (ψ), the plastic potential eccentricity of concrete (ε), the ratio of compressive stress in the biaxial state to the compressive stress in the uniaxial state (σ_{b0}/σ_{c0}), the shape factor of yielding surface in the deviatoric plane (Kc) and viscosity parameter. The values of all these parameters were obtained from calibration. These plates had been thought-about as rigid components with young's modulus of 210 GPa and density of 7.85x10-9 ton/mm^3.The stress vs stress Curve for compression (Eurocode 2) and Nayal and Rasheed tension stiffening model of Concrete (2006) [25], changed for 500^{0}C is used as input for heated unconfined concrete as shown in Figures 5(a) and 5(b) respectively. The properties of concrete that were finalized during calibration of model are given in Table 2.The seeding/Mesh size selected is 20 mm during calibration of model. Dilation angle is a material parameter and physically, it is interpreted as an internal friction angle of concrete. The Kc (Shape factor) with a value of 0.667 is best suited for the plastic behaviour of concrete recommended by the CDP model.

Table 1. Element mesh types selected (Finalized)

Parts	Element Mesh Type Chosen	Interactions	
Concrete Column	C3D8R	Top of Concrete Column as Slave surface	Bottom of concrete column as Master Surface
Longitudinal steel	T3D2	Embedded in concrete	
Transverse steel	T3D2	Embedded in concrete	
Steel Plate	C3D8R	Bottom of Top plate as Master surface	Top of Bottom plate as slave surface

Table 2. Material properties finalised during calibration of model for simulation of damaged concrete

Parameters	Values
Poisson's ratio, ν	0.2
Dilation Angle	35
Concrete cover (mm)	20
Initial and maximum increment size of the loading	0.01
Minimum increment size	10^{-10}
E_{cc}	0.1
f_{bo}/f_{c0}	1.16
k	0.67
Viscosity Parameter	$1*10^{-5}$

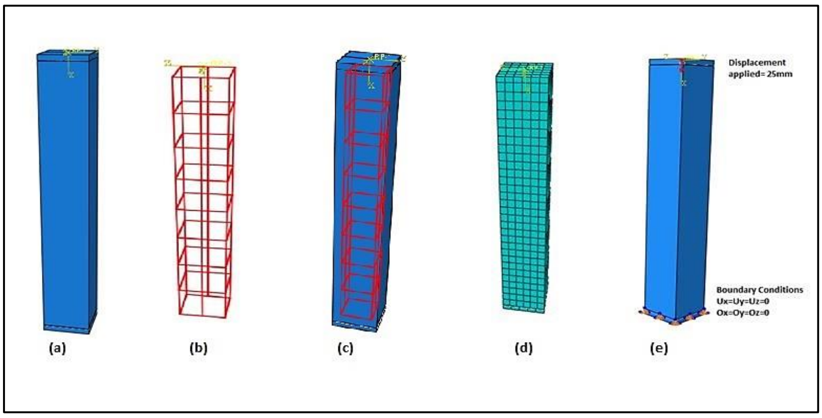
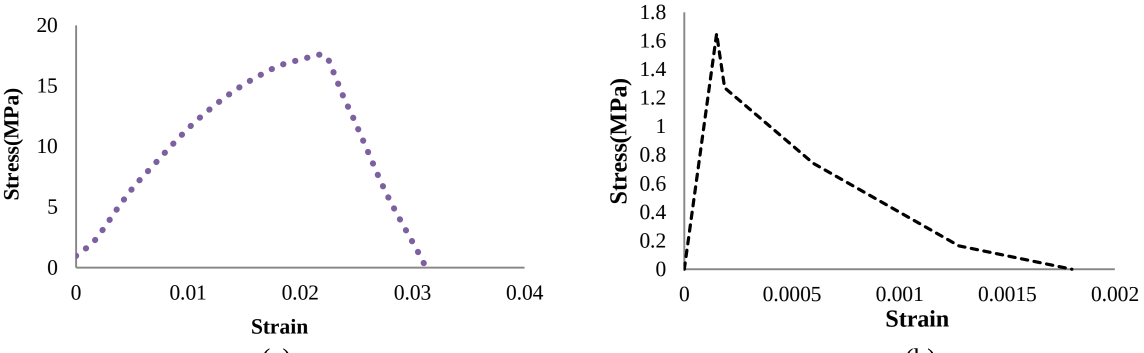


Figure 4. (a) Solid homogenous section; (b) Reinforcement; (c) Reinforcement embedded in concrete; (d) FE mesh; (e) Boundary conditions



(a) (b)

Figure 5. (a) Stress vs Strain curve for compression 500 ^{0}C; Eurocode Code 2; (b) Nayal and Rasheed tension stiffening model of Concrete (2006), modified for 500 ^{0}C

4.1. Simulation of Reinforcement

The elastic behaviour of steel of steel is defined as given in Table 3. The nonlinear behavior is simulated by the use of a strain hardening ratio of zero.01 as encouraged by Kachlakev et al. (2018) [26] as shown in Figure 6.

Table 3. Elastic properties of Steel used as input

Property	Value
Density	7.85E-009(ton/mm^3)
Young's Modulus	210000 (GPa)
Poison's ratio	0.3

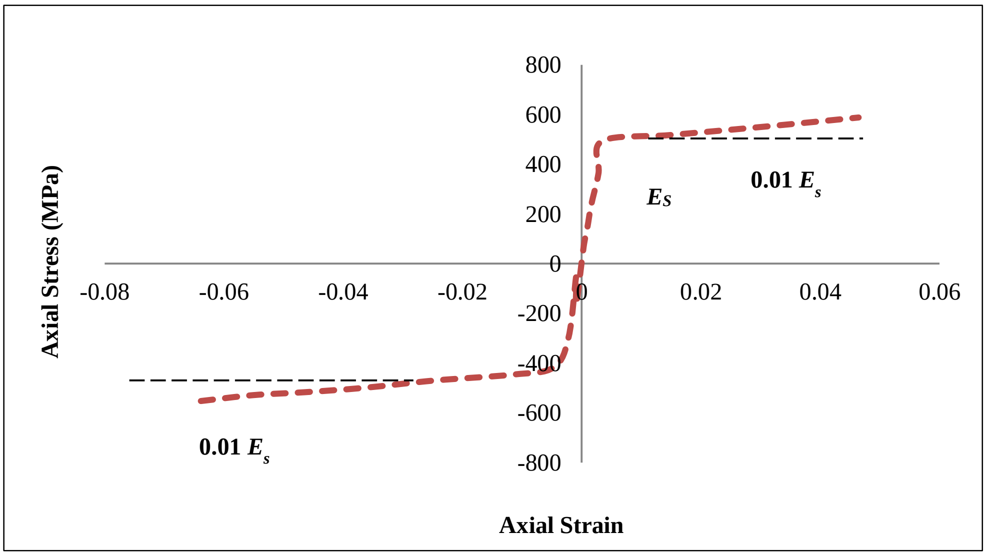


Figure 6. Bilinear stress-strain behaviour of steel bars

5. Parametric Study

In order to investigate the behavior of viscosity parameter on numerical simulation of post heated RC square Column, a parametric study is performed. For this purpose 7 different models are created, tabulated in Table 3. Results are compared in the form of load deformation Curves.

6. Results and Discussions

The predictions made by Abaqus Model are very close to that of experimental. S3M3 results showed that best fit model is developed with difference of only 2.43% of experimental and modelled values. The overestimated values are represented by negative sign under the percentage diff. column in Table 4. Excellent predictions are made by models except those for higher values of viscosity parameter for Post heated 500 °C unconfined RC columns. The Principle strains shown in Figure 7 are for model S3M3 that showed best fit curve for load vs deformation plotting. The values of strain are more for heated concrete than that of controlled specimen's i-e undamaged concrete. Maximum stresses are recorded at mid principle axis reported as 0.0015 shown by red graphics in figure.

Parametric study showed that the total number of iterations to finish the FE analysis and percentage of convergence according to step time are specified in Table 3. Moreover, ultimate load values of the test and numerical models are given, and error of numerical results in Load (KN) is compared with the test result in the Table 4. It can be clearly seen from Figure 9 that viscosity parameter plays very important role on numerical results in a way that it changes significantly the numerical load-displacement behavior of heat damaged RC columns. However load-displacement graphs could not be obtained for models S3M1 and S3M2 because the FE models did not converged. The FE model S3M1aborted with very small percentage of convergence (6%) under value of viscosity parameter, zero which is a default value of ABAQUS software. Moreover with the definition of a very small viscosity parameter to the FE model, S3M2, the simulation similarly did not converged but the percentage of convergence has slightly increased (15%). Due to no convergent results, duration of analysis (total number of iteration) could not be measured for that FE model.

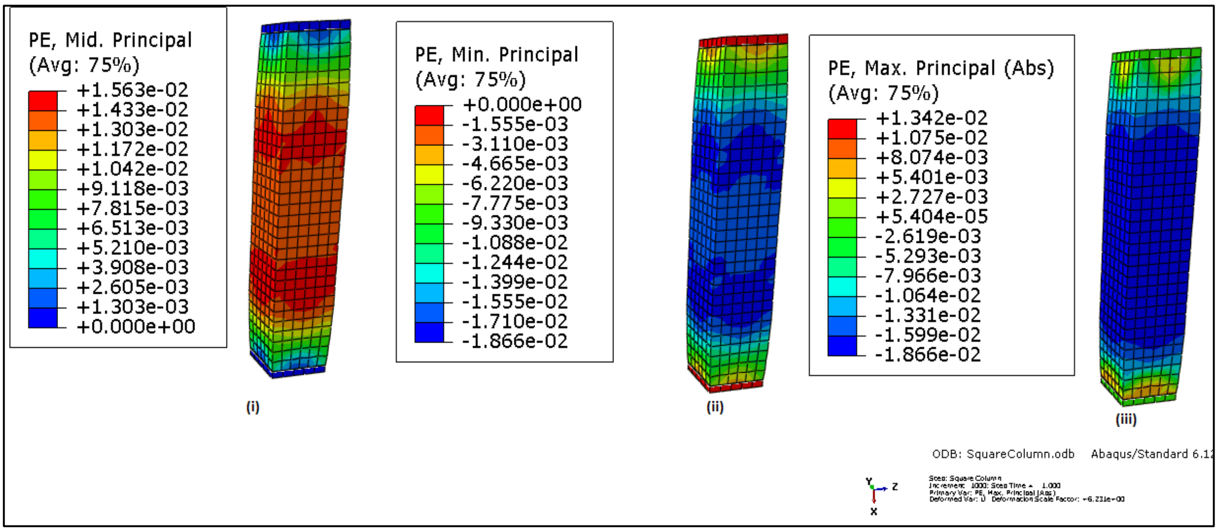


Figure 7. (i) Mid Principle, PE, (ii) Minimum Principle, PE (iii) Maximum principle , PE

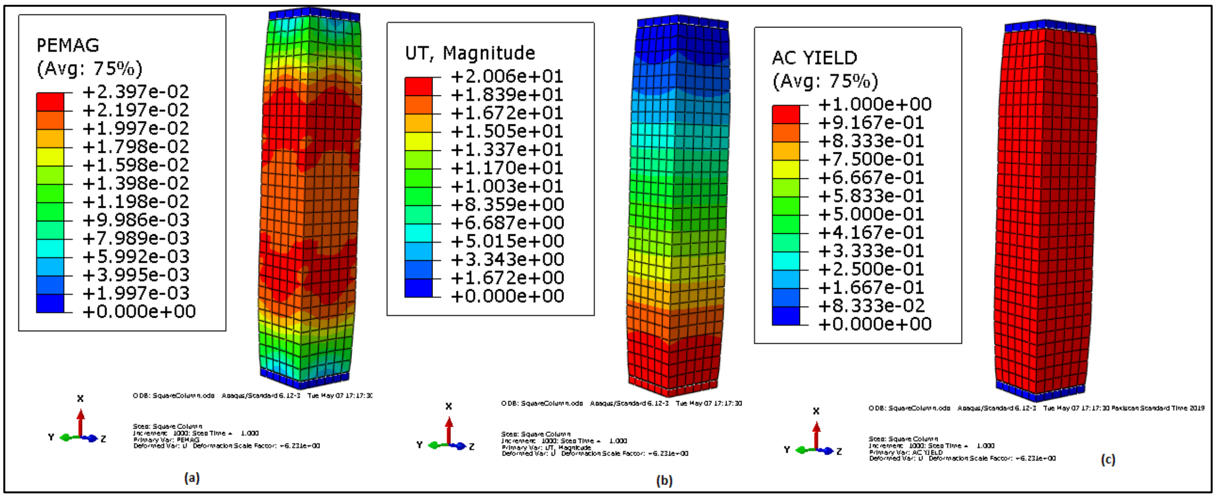


Figure 8. (a) Plastic strain Magnitude, (b) Translation displacement, (c) Active Yield (AC Yield)

Table 4. Results of the experimental and numerical study

Name of Model	μ	Total iterations	Convergence (%)	Load (KN)	Diff (%)
S3	-	-	-	864	-
S3M1	0	n/a	6	n/a	n/a
S3M2	0.00001	n/a	15	n/a	n/a
S3M3	0.00005	1211	100	843	2.430556
S3M4	0.0001	1048	100	893	-3.35648
S3M5	0.0005	1000	100	915	-5.90278
S3M6	0.001	848	100	933	-7.98
S3M7	0.01	456	100	1211	-40.1

With the increase in value of **μ**, numerical models have started to converge. For the models, S3M3 and S3M4, the numerical results are very similar to that of experimental in terms of load-displacement behavior of the tested damaged RC columns. Percentage of error in ultimate load level stayed under 5 % as well. Total number of iterations for S3M3 and S3M4 are 1211 and 1048 respectively. Numerical load-deformation behaviors of the models of S3M5 through S3M7 have started to lose their fitness due to increase in value of viscosity parameter (above 0.0005). When the value of μ, is above 0.005, the models of S3M6 and S3M7 showed very weak behavior and the results substantially deviated from that of experimental. However total number of iterations decreased significantly. Plastic strain magnitude is abbreviated as, PEMAG. For most of the material this magnitude is equal to Equivalent plastic strain. Figure 8(a) shows the values of plastic strain magnitude. PEMAG is maximum at the centre of column and reduces up to the top and bottom. UT, that represent all translation displacement components is shown in Figure 8(b). Active yield (AC Yield) is an important parameter showing that plastic flow has taken place in simulation after application of load. The value of AC Yield 1 confirms plastic flow while AC value 0 shows no plastic flow region as shown in Figure 8(c).

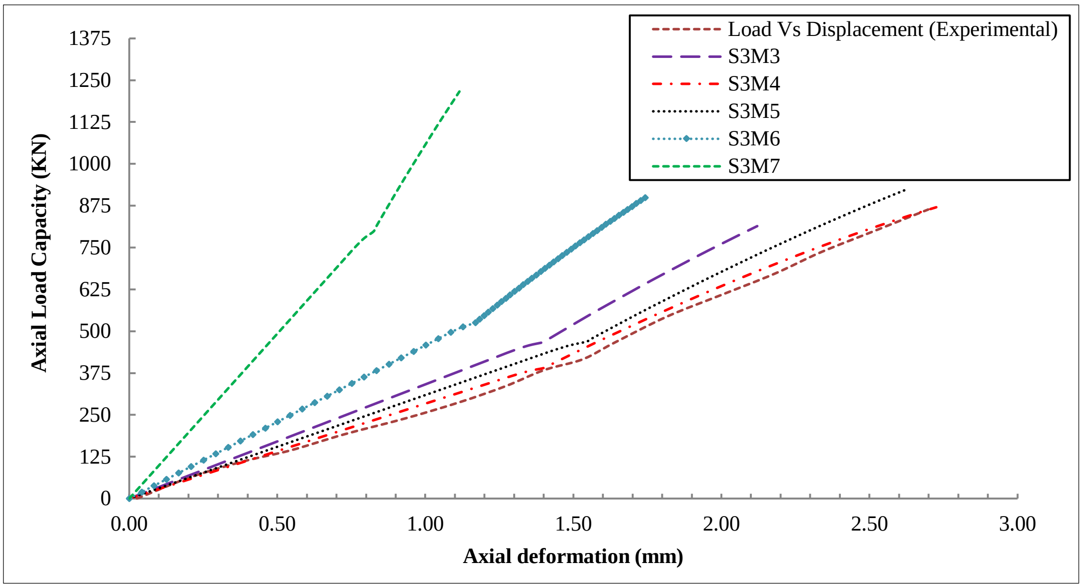


Figure 9. Load-displacement results Comparison for different models

7. Conclusion

The numerical verification of existing experimental study was carried out in order to investigate the sensitivity of viscosity parameter. The results were compared in terms of load displacement relationship, time and rate of convergence. Following conclusions are drawn from the study performed.

- Optimum value of viscosity parameter that reduces time and increases convergence should be selected.
- The optimum value of 0.00005 or 0.0001 should be selected as it gives excellent fit model for heated damaged unjacketed RC Square Columns.
- Above 0.0005 the values divert a lot so its use is discouraged though it reduces time and increments.
- Study should be conducted with varied values of the parameter in order to improve calculation accuracy of numerical simulation of post heated unconfined RC square columns.

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9. Conflict of Interest

The authors declare no conflict of interest.

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