4.0 THEORETICAL INVESTIGATIONS

4.1 General

Analytical model was developed to verify and validate the results obtained based on detailed experimental investigations performed on HPC square columns reinforced GFRP and steel to study the effect of reinforcement and L/D ratio on parameters such as axial deformation, lateral deformation and rebar strain using finite element software ANSYS. Output of analytical model developed for both GFRP and steel reinforced columns and the corresponding results are discussed in this chapter.

4.2 Finite Element Modeling

4.2.1 Introduction

Nowadays, latest generation research and commercial finite element codes are capable of simulating almost all the complex phenomena. However, difficulties still remain for the numerical analyst who has to choose appropriate finite element models able to provide an accurate representation of the physics at the lowest computational cost. For the present research work, three dimensional finite element analysis software, ANSYS 8.0 was used to create the model of the column.

4.2.2 Model

Assumption and simplifications were made in order to avoid detailed modeling and reduce the computational effort. ANSYS first order solid hexahedral elements SOLID 65, The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z direction with incompatible displacement modes were used to model the connection geometry. Link 8 the 3-D spar element is a uniaxial tension-compression element with three degrees of freedom at each node: translations in the nodal x, y, and z directions and pipe 16The element has six degrees
of freedom at two nodes: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes.

### 4.2.3 Meshing

The technique of FEA lies in the development of a suitable mesh arrangement. The mesh discretisation must balance the need for a fine mesh to give an accurate stress distribution and reasonable analysis time. Mapped mesh used for meshing. Compared to a free mesh, a mapped mesh is restricted in terms of the element shape it contains and the pattern of the mesh. A mapped area mesh contains either only quadrilateral or only triangular elements, while a mapped volume mesh contains only hexahedron elements. In addition, a mapped mesh typically has a regular pattern, with obvious rows of elements. If you want this type of mesh, you must build the geometry as a series of fairly regular volumes and/or areas that can accept a mapped mesh. The finite element height has taken as 50 mm and breadth 10 mm x 10 mm. Fig. 4.1 shows the modeled and meshing.

![Fig. 4.1 Modeling and Meshing](image-url)
4.2.4 Element description

Solid 65

Brick elements, as called Solid 65 in ANSYS, were used in three-dimensional modeling of column. The use of these elements provides the same number of integration point density as the higher-order elements but require much less computational power. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities with the addition of special cracking and crushing capabilities. The most important aspect of this element is the treatment of nonlinear material properties. The concrete is capable of cracking (in three orthogonal directions), crushing, plastic deformation, and creep. The rebar are capable of tension and compression.

Geometrical views of Solid 65 elements are given in Fig. 4.2.

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**Input summary**

**Nodes**

I, J, K, L, M, N, O, P

**Degrees of Freedom**
UX, UY, UZ

**Real Constants**
- MAT1, VR1, THETA1, PHI1, MAT2, VR2, THETA2, PHI2, MAT3, VR3, THETA3, PHI3, CSTIF

**Material Properties**
- EX, ALPX (or CTEX or THSX), PRXY or NUXY, DENS (for concrete)
- EX, ALPX (or CTEX or THSX), DENS (for each rebar)

**Surface Loads**
- **Pressures --**
  - face 1 (J-I-L-K), face 2 (I-J-N-M), face 3 (J-K-O-N), face 4 (K-L-P-O), face 5 (L-I-M-P), face 6 (M-N-O-P)

**Body Loads**
- **Temperatures --**
  - T(I), T(J), T(K), T(L), T(M), T(N), T(O), T(P)
- **Fluences --**
  - FL(I), FL(J), FL(K), FL(L), FL(M), FL(N), FL(O), FL(P)

**Special Features**
- Plasticity
- Creep
- Cracking
- Crushing
- Large deflection
- Large strain
- Stress stiffening
- Birth and death
- Adaptive descent

### 4.2.5 Link 8

LINK8 is a spar, which may be used, in a variety of engineering applications. This element can be used to model trusses, sagging cables, links, springs, etc. The 3-D spar element is a uniaxial tension-compression element with three degrees of freedom at each node: translations in the nodal x, y, and z directions. As in a pin-jointed
structure, no bending of the element is considered. Plasticity, creep, swelling, stress stiffening, and large deflection capabilities are included. Geometrical views of Link 8 elements are given in Fig. 4.3.

Fig. 4.3 Geometrical views of Link 8 elements

Input Summary

Nodes

I, J

Degrees of Freedom

UX, UY, UZ

Real Constants

AREA - Cross-sectional area
ISTRN - Initial strain

Material Properties

EX, ALPX (or CTEX or THSX), DENS, DAMP

Surface Loads

None

Body Loads

Temperatures --

T(I), T(J)

Fluences --
Special Features
Plasticity
Creep
Swelling
Stress stiffening
Large deflection
Birth and death

4.2.6 Pipe 16

PIPE16 is an uniaxial element with tension-compression, torsion, and bending capabilities. The element has six degrees of freedom at two nodes: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes. Geometrical views of Pipe 16 elements are given in Fig. 4.4.

Fig. 4.4 Geometrical views of Pipe 16 elements

Input Summary

Nodes
I, J, K (K, the orientation node, is optional)

Degrees of Freedom
UX, UY, UZ, ROTX, ROTY, ROTZ

Real Constants
OD, TKWALL, SIFI, SIFJ, FLEX, DENSFL,
DENSIN, TKIN, TKCORR, AREAIN, MWALL, STIFF,
SPIN

Material Properties
EX, ALPX (or CTEX or THSX),
PRXY (or NUXY), DENS, GXY, DAMP

Surface Loads
Pressures --
1-PINT, 2-PX, 3-PY, 4-PZ, 5-POUT

Body Loads
Temperatures --
TOUT(I), TIN(I), TOUT(J), TIN(J) if KEYOPT (1) = 0, or
TAVG(I), T90(I), T180(I), TAVG(J), T90(J), T180(J) if KEYOPT (1) = 1

Special Features
Stress stiffening
Large deflection
Birth and death

4.2.7 Load and Boundary conditions

The models were assumed to be simply supported in plane, the ends are fixed against
horizontal and vertical displacement and rotation restrained against vertical axis only
but bottom end vertical displacement unrestrained for applying load.

4.2.8 Newton Raphson procedure

![Newton Raphson Approach](image_url)

Fig. 4.5 Newton Raphson Approach
ANSYS employs the Newton-Raphson approach to solve non-linear problems. In this approach the load is subdivided into a series of load increments. The load increments can be applied over several load steps. Newton-Raphson Approach shown in Fig. 4.5 and illustrates the use the Newton-Raphson equilibrium iterations in a single DOF non-linear analysis. Before each solution, the Newton-Raphson method evaluates the out of balance load vector, which is the difference between the restoring forces (the loads corresponding to the element stresses) and the applied loads. The program then performs a linear solution, using the out-of-balance and checks for convergence. If convergence criteria are not satisfied, the out-of-balance load vector is re-evaluated, the stiffness matrix updated, and a new solution is obtained. This iterative procedure continues until the problem converges. A number of convergence-enhancement and recovery features, such as line search, automatic load stepping, and bisection, can be activated to help the problem to converge. If convergence cannot be achieved, then the program attempts to solve with a smaller load increment.

4.3 Finite Element Model output for an axial deformation

The output obtained from the finite element model for an axial deformation both for GFRP and Steel reinforced column for different L/D ratio with three different percentages of reinforcement are given separately. For each L/D ratio, there are three outputs were taken and are depicted in figures (a), (b) and (c) as sub divisions for 1.4%, 2% and 3.5% reinforcement respectively. These outputs are depicted in Figs.4.6 to 4.9 for GFRP reinforced columns with L/D ratio 6, 8, 10 and 12 and for steel reinforced columns, Figs. 4.10 to 4.13 can be referred for the similar L/D ratios.

4.4 Axial deformation of GFRP reinforced Column- Effect of reinforcement

The variation of axial deformation of GFRP reinforced column for L/D = 6, 8, 10 and 12 with three different percentages of reinforcement are shown in the Figs. 4.14 to
4.17 to study the effect of reinforcement on axial deformation. It is observed from the results that increase in percentage of reinforcement decreases the axial deformation irrespective of L/D ratio of the column. It is also observed that the axial deformation increases with increase in L/D ratio for the given percentage of reinforcement. For L/D ratio 6, the axial deformation values are 5.7 mm, 6.46 mm and 6.94 mm respectively for 3.5%, 2% and 1.4% reinforcement. These values are 7.04 mm, 8.22 mm and 10.02 mm, 9.8 mm, 11.44 mm and 12.39 mm, 11.69 mm, 13.64 mm and 14.77 mm for L/D ratios 8, 10 and 12 respectively. The rate of reduction in axial deformation varies from 7 to 18% due to increase in reinforcement from 1.4 to 2% and 12 to 15% due to increase in reinforcement from 2 to 3.5%.

4.5 Axial deformation of GFRP reinforced Column- Effect of L/D ratio
The variation of axial deformation of GFRP reinforced column for 1.4%, 2% and 3.5% reinforcement with four L/D ratios are shown in the Figs. 4.18 to 4.20 to study the effect of L/D ratio on axial deformation. Axial deformation increases with increase in L/D ratio for all percentages of reinforcement indicating the slenderness effect. Due to increase in L/D ratio, the rate of increase in axial deformation is 44% for L/D = 6 to 8, 24% for L/D = 8 to 10 and 19% for L/D = 10 to 12 with 1.4% reinforcement. These values are 27% for L/D = 6 to 8, 39% for L/D = 8 to 10 and 19% for L/D = 10 to 12 and 23% for L/D = 6 to 8, 39% for L/D = 8 to 10 and 19% for L/D = 10 to 12 with 2% reinforcement and 3.5% reinforcement respectively.

4.6 Lateral deformation of GFRP reinforced Column-Effect of reinforcement
The variation of lateral deformation of GFRP reinforced column for L/D = 6, 8, 10 and 12 with three different percentages of reinforcement are shown in the Figs. 4.21 to 4.24 to study the effect of reinforcement on lateral deformation. The graphs are plotted between deformation versus location of LVDT. It is observed from the results
that increase in percentage of reinforcement decreases the lateral deformation irrespective of L/D ratio of the column. It is also observed that the lateral deformation increases with increase in L/D ratio for the given percentage of reinforcement. In general, the quantum of lateral deformation is found to be less, since the columns were subjected to axial loading. Lesser deformation was noticed on either LVDTs located at nearer from the end and higher deformation was observed in the middle three locations of LVDTs. A maximum deformation of 0.08 mm, 0.07 mm and 0.06 mm was observed for columns with reinforcement of 1.4, 2 and 3.5% for L/D = 12.

### 4.7 Lateral deformation of GFRP reinforced Column- Effect of L/D ratio

The variation of lateral deformation of GFRP reinforced column for 1.4%, 2% and 3.5% reinforcement with four L/D ratios are shown in the Figs. 4.25 to 4.27 to study the effect of L/D ratio on lateral deformation. Lateral deformation increases with increase in L/D ratio for all percentages of reinforcement indicating the slenderness effect. Here also similar trend was observed regarding lateral deformation with respect to location of LVDTs as earlier seen with effect of reinforcement.

### 4.8 Rebar axial strain of GFRP reinforced Column- Effect of reinforcement

The variation of rebar axial strain of GFRP reinforced column for L/D = 6, 8, 10 and 12 with three different percentages of reinforcement are shown in the Figs. 4.28 to 4.31 to study the effect of reinforcement on rebar axial strain. It is observed from the results that increase in percentage of reinforcement decreases the rebar axial strain irrespective of L/D ratio of the column. It is also observed that the rebar axial strain increases with increase in L/D ratio for the given percentage of reinforcement. Almost for all the cases, similar trend was observed as noticed in the axial deformation. A maximum strain of 0.00395 was observed for the column with 1.4% reinforcement and L/D ratio of 12.
4.9  **Rebar axial strain of GFRP reinforced Column- Effect of L/D ratio**

The variation of rebar axial strain of GFRP reinforced column for 1.4%, 2% and 3.5% reinforcement with four L/D ratios are shown in the Figs. 4.32 to 4.34 to study the effect of L/D ratio on rebar axial strain. Rebar axial strain little bit increases with increase in L/D ratio for all percentages of reinforcement indicating the slenderness effect and in general it is less significant.

4.10  **Axial deformation of Steel reinforced Column- Effect of reinforcement**

The variation of axial deformation of steel reinforced column for L/D = 6, 8, 10 and 12 with three different percentages of reinforcement are shown in the Figs. 4.35 to 4.38 to study the effect of reinforcement on axial deformation. It is observed from the results that increase in percentage of reinforcement decreases the axial deformation irrespective of L/D ratio of the column. It is also observed that the axial deformation increases with increase in L/D ratio for the given percentage of reinforcement. For L/D ratio 6, the axial deformation values are 6.91 mm, 6.42 mm and 5.54 mm respectively for 1.4%, 2% and 3.5% reinforcement. These values are 9.97 mm, 8.15 mm and 6.98 mm, 12.34 mm, 11.38 mm and 9.72 mm, 14.7 mm, 13.56 mm and 11.6 mm for L/D ratios 8, 10 and 12 respectively. The rate of reduction in axial deformation varies from 7 to 18% due to increase in reinforcement from 1.4 to 2% and is about 15% due to increase in reinforcement from 2 to 3.5%.

4.11  **Axial deformation of Steel reinforced Column- Effect of L/D ratio**

The variation of axial deformation of steel reinforced column for 1.4%, 2% and 3.5% reinforcement with four L/D ratios are shown in the Figs. 4.39 to 4.41 to study the effect of L/D ratio on axial deformation. Axial deformation increases with increase in L/D ratio for all percentages of reinforcement indicating the slenderness effect. Due to increase in L/D ratio, the rate of increase in axial deformation is 44% for L/D = 6 to
8, 23% for L/D = 8 to 10 and 19% for L/D = 10 to 12 with 1.4% reinforcement. These values are 27% for L/D = 6 to 8, 39% for L/D = 8 to 10 and 19% for L/D = 10 to 12 and 26% for L/D = 6 to 8, 39% for L/D = 8 to 10 and 19% for L/D = 10 to 12 with 2% reinforcement and 3.5% reinforcement respectively.

4.12 Lateral deformation of Steel reinforced Column- Effect of reinforcement

The variation of lateral deformation of steel reinforced column for L/D = 6, 8, 10 and 12 with three different percentages of reinforcement are shown in the Figs. 4.42 to 4.45 to study the effect of reinforcement on lateral deformation. The graphs are plotted between deformations versus location of LVDT. It is observed from the results that increase in percentage of reinforcement decreases the lateral deformation irrespective of L/D ratio of the column. It is also observed that the lateral deformation increases with increase in L/D ratio for the given percentage of reinforcement. Lesser deformation was noticed on either LVDTs located at nearer quarters from the end and higher deformation was observed in the middle three LVDTs. A maximum deformation of 0.07 mm, 0.06 mm and 0.04 mm was observed for columns with reinforcement of 1.4, 2 and 3.5% for L/D = 12.

4.13 Lateral deformation of Steel reinforced Column- Effect of L/D ratio

The variation of lateral deformation of steel reinforced column for 1.4%, 2% and 3.5% reinforcement with four L/D ratios are shown in the Figs. 4.46 to 4.48 to study the effect of L/D ratio on lateral deformation. Lateral deformation increases with increase in L/D ratio for all percentages of reinforcement indicating the slenderness effect. Here also similar trend was observed as GFRP reinforced column with respect to location of LVDTs as earlier seen with effect of reinforcement.
4.14 Rebar axial strain of Steel reinforced Column- Effect of reinforcement

The variation of rebar axial strain of steel reinforced column for L/D = 6, 8, 10 and 12 with three different percentages of reinforcement are shown in the Figs. 4.49 to 4.52 to study the effect of reinforcement on rebar axial strain. It is observed from the results that increase in percentage of reinforcement decreases the rebar axial strain irrespective of L/D ratio of the column. It is also observed that the rebar axial strain increases with increase in L/D ratio for the given percentage of reinforcement. Lesser variation in rebar axial strain was noticed among the different percentages of reinforcement for L/D = 6. However, almost for all the other cases, similar trend was observed as noticed in the axial deformation. A minimum strain of 0.00275 was observed for the column with 3.5% reinforcement for L/D ratio of 8 and a maximum strain of 0.00393 was observed for the column with 1.4% reinforcement for L/D ratio of 12.

4.15 Rebar axial strain of Steel reinforced Column- Effect of L/D ratio

The variation of rebar axial strain of steel reinforced column for 1.4%, 2% and 3.5% reinforcement with four L/D ratios are shown in the Figs. 4.53 to 4.55 to study the effect of L/D ratio on rebar axial strain. Rebar axial strain little bit increases with increase in L/D ratio for all percentages of reinforcement indicating the slenderness effect and in general it is less significant.

Detailed discussion on comparison of experimental and analytical results of both GFRP and Steel reinforced columns are given in the Chapter 5.
Fig. 4.6 FEM output for axial deformation of GFRP column for L/D=6
(a) For 1.4% reinforcement

(b) For 2% reinforcement

(c) For 3.5% reinforcement

Fig. 4.7 FEM output for axial deformation of GFRP column for L/D=8
Fig. 4.8 FEM output for axial deformation of GFRP column for L/D=10

(a) For 1.4% reinforcement

(b) For 2% reinforcement

(c) For 3.5% reinforcement
Fig. 4.9 FEM output for axial deformation of GFRP column for L/D=12
(a) For 1.4% reinforcement

(b) For 2% reinforcement

(c) For 3.5% reinforcement

Fig. 4.10 FEM output for axial deformation of Steel reinforced column for L/D=6
(a) 1.4% reinforcement

(b) 2% reinforcement

(c) 3.5% reinforcement

Fig. 4.11 FEM output for axial deformation of Steel reinforced column for L/D=8
Fig. 4.12 FEM output for axial deformation of Steel reinforced column for L/D=10

(a) 1.4% reinforcement

(b) 2% reinforcement

(c) 3.5% reinforcement
Fig. 4.13 FEM output for axial deformation of Steel reinforced column for L/D=12

(a) 1.4% reinforcement

(b) 2% reinforcement

(c) 3.5% reinforcement
Fig. 4.14 Load vs axial deformation for GFRP reinforced column with L/D = 6

Fig. 4.15 Load vs axial deformation for GFRP reinforced column with L/D = 8
Fig. 4.16 Load vs axial deformation for GFRP reinforced column with L/D = 10

Fig. 4.17 Load vs axial deformation for GFRP reinforced column with L/D = 12
Fig. 4.18 Load vs axial deformation for GFRP column with 1.4% reinforcement

Fig. 4.19 Load vs axial deformation for GFRP column with 2% reinforcement
Fig. 4.20 Load vs axial deformation for GFRP column with 3.5% reinforcement

Fig. 4.21 Load vs lateral deformation for GFRP reinforced column with L/D = 6
Fig. 4.22 Load vs lateral deformation for GFRP reinforced column with L/D = 8

Fig. 4.23 Load vs lateral deformation for GFRP reinforced column with L/D = 10
Fig. 4.24 Load vs lateral deformation for GFRP reinforced column with $L/D = 12$

Fig. 4.25 Load vs lateral deformation for GFRP column with 1.4% reinforcement
Fig. 4.26 Load vs lateral deformation for GFRP column with 2% reinforcement

Fig. 4.27 Load vs lateral deformation for GFRP column with 3.5% reinforcement
Fig. 4.28 Load vs rebar axial strain for GFRP reinforced column with L/D = 6

Fig. 4.29 Load vs rebar axial strain for GFRP reinforced column with L/D = 8
Fig. 4.30 Load vs rebar axial strain for GFRP reinforced column with L/D = 10

Fig. 4.31 Load vs rebar axial strain for GFRP reinforced column with L/D = 12
Fig. 4.32 Load vs rebar axial strain for GFRP column with 1.4% reinforcement

Fig. 4.33 Load vs rebar axial strain for GFRP column with 2% reinforcement
Fig. 4.34 Load vs rebar axial strain for GFRP column with 3.5% reinforcement

Fig. 4.35 Load vs axial deformation of Steel reinforced column with L/D = 6
Fig. 4.36 Load vs axial deformation of Steel reinforced column with L/D = 8

Fig. 4.37 Load vs axial deformation of Steel reinforced column with L/D = 10
Fig. 4.38 Load vs axial deformation of Steel reinforced column with L/D = 12

Fig. 4.39 Load vs axial deformation of Steel reinforced column with 1.4% reinforcement
Fig. 4.40 Load vs axial deformation of Steel reinforced column with 2% reinforcement

Fig. 4.41 Load vs axial deformation of Steel reinforced column with 3.5% reinforcement
Fig. 4.42 Load vs lateral deformation of Steel reinforced column with L/D = 6

Fig. 4.43 Load vs lateral deformation of Steel reinforced column with L/D = 8
Fig. 4.44 Load vs lateral deformation of Steel reinforced column with L/D = 10

Fig. 4.45 Load vs lateral deformation of Steel reinforced column with L/D = 12
Fig. 4.46 Load vs lateral deformation of Steel reinforced column with 1.4% reinforcement

Fig. 4.47 Load vs lateral deformation of Steel reinforced column with 2% reinforcement
Fig. 4.48 Load vs lateral deformation of Steel reinforced column with 3.5% reinforcement

Fig. 4.49 Load vs rebar axial strain of Steel reinforced column with L/D = 6
Fig. 4.50 Load vs rebar axial strain of Steel reinforced column with L/D = 8

Fig. 4.51 Load vs rebar axial strain of Steel reinforced column with L/D = 10
**Fig. 4.52 Load vs rebar axial strain of Steel reinforced column with L/D = 12**

**Fig. 4.53 Load vs rebar axial strain of Steel reinforced column with 1.4% reinforcement**
Fig. 4.54 Load vs rebar axial strain of Steel reinforced column with 2% reinforcement

Fig. 4.55 Load vs rebar axial strain of Steel reinforced column with 3.5% reinforcement