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Performance Based Analysis of Shear Wall with Flexible Soil Base

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ABSTRACT

Shear wall is usually modeled with different types of elements with fixed base to tolerate lateral load. Membrane, plate and shell elements are chosen to model shear wall without reinforcement. In the present study an attempt is made on a 3D, 10 storey building with flexible soil base. The building is analyzed with and without shear wall. The shear wall is provided at all four corners throughout the height of the building. The building is resting on flexible soil base and analyzed for nonlinear analysis. The shear wall is modeled with different elements and different number of layer section (i.e., concrete and steel layers). Shear wall is modeled separately with membrane, plate and shell elements. In addition to this combination of elements is also tried to model shear wall. The combination to model shear wall chosen is plate and membrane element with variation in number of concrete and steel layers. This study is helpful to predict response of shear wall provided with various elements. It gives us idea as to model shear wall with elements separately or in combination. The behavior of shear wall modeled with variation in concrete and steel layers is also predicted.

Keywords : Shear wall , Nonlinear analysis , Flexible base.

I. INTRODUCTION

As we know shear wall is provided to tolerate lateral load. Before discussing about the present study it is very important to know about few technical terms in order to give better understanding.

1.1. Shear wall modeled with various elements and its behavior:

The shear wall modeled with various elements will be subjected to various type of bending such as "In plane bending. In case of in plane bending the plates bend in its own plane. Shear wall with horizontal and vertical forces applied to its plane produces in plane bending moment. Whereas, Out of plane bending is the bending moment which is caused by out of plane forces such as a building slab. Similarly In plane loading is loading acting long the axis of the surface (say axis of slab or axis of wall) whereas, Out of plane loading is loading perpendicular of the surface(wind or earthquake load). In plane stiffness affects strongly the structural behavior of existing building subjected to seismic action. It defines the seismic distribution of forces on the lateral walls. Inadequate in plane stiffness of the floor causes overturning of the walls perpendicular to the seismic action. Other type of effect which shear wall under goes is stiffness. Stiffness is the ability of resistance to deflection. More stiff or rigid means more force is required to produce unit displacement or it is the resistance offered by a structure while undergoing bending. There are two kinds of stiffness one is Axial Stiffness (is more in truss) which is the force required to produce unit displacement. Other stiffness is bending or Flexural stiffness (its more in beam) which is the moment required producing unit rotation".

Axial Stiffness =EA/L, Bending stiffness=EI/L, Bending stress: σb=My/I, Stiffness: K =P/w (force /deflection)
Stiffness=Force/Unit Displacement

In addition, let us see in brief the behavior of various elements individually. "Plate element, a plate can bend. Plate sustains out of plane loading by bending stress and is a structural member which adds flexural stiffness. In addition to transverse load carrying capacity, plates can withstand lateral load by bending stiffness. Membrane element, a membrane cannot bend. It can resist forces by in plane tension (i.e., transferring load to the supports by tension). Membrane has in plane stiffness and sustain out of plane loading by in plane stresses. Example: The cable between two support pillars is the membrane or take the clothe and put it on the cable to dry. The cable takes load by transferring load to supports. Load which is applied to membrane transfers directly to supporting structural objects, hence 100% of load is transferred in membrane. Or one can say a membrane is like thin rubber sheet which can carry transverse load through in plane tension. Membrane elements are used to represent only in plane stiffness of member. It acts like bed sheet on your bed. The bed sheet does not have any kind of bending stiffness and so it bends without any resistance. So use this kind of element in slabs or any other plates to resist bending i.e., they are called as out of plane bending. Membranes are plates with zero flexural stiffness. But they do posses in plane stiffness they can carry axial forces. In more detail, the difference between a membrane and a plate is given by moment of resistance. The membrane thickness is very small so it cannot take bending. A membrane is a structural element which has in plane stiffness but not flexural stiffness. In other words the membrane can resist lateral load but they cannot tolerate any bending moment. Lastly a shell element is a combination of a plate and a membrane. Shell objects have bending stiffness and therefore resist portion of the load through flexural deformation. As a result fewer loads are available to transfer to the beams located under a shell. From FEM perspective, Plate elements have 3 degree of freedom per node. Out of 3 dof, 2 dof are in plane rotations and 1 dof corresponds to the out of plane translation. (θx, θy (in plane rotation) +Uz (out of plane translation). Whereas, membrane elements also have 3 dof per node, out of which 2 dof are in plane translation and 1 dof corresponds to out of plane rotation. (Ux, Uy (in plane translation) + θz (out of plane rotation). When we design slab as membrane element, the slab only receives in plane forces and not resisting any bending moment. This means, all the bending moments are transferred to the beam. "Shell elements combine plate and membrane elements, meaning they have 6 dof per node. All three in plane translation and rotation along all axes. This is the reason why it is commonly used." (Curtsey taken from practical aspect of finite element simulation: a study guide, Altair University).

Shell elements are more realistic for any structural wall or a slab or basement wall or even thick pipe. They have in plane as well as out of plane stiffness. Shells have both flexural as well as axial stiffness. Shell elements have both bending as well as in plane stiffness. Shells can resist moments and forces from all direction. Shells are further divided into thin and thick shells based on their minimum length to thickness ratio. There is difference in theoretical part like thick shells are assumed to have shear deformation (mindlin theory) whereas thin shells do not undergo shear deformation (krichhof's love theory). The primary difference between thin shells and plates is in terms of their curvature. Thin shells have curvature, whereas plates are flat. When shear wall is modeled as shell element, the shear wall is resisting moments as well as forces".

Shell = Plate +Membrane

(Ux, Uy, Uz, θx.θy, θz) = Uz, θx, θy+Ux, Uy, θz) i.e., (3T+3R) = (1T+2R) + (2T+1R)

Nonlinear FEM model for RC shear wall is modeled based on layer sections. The layer sections are made up of many layers with different thickness and different material such as concrete and steel

II. METHODOLOGY

Shear wall is modeled in SAP 2000 V19.2.1 software. The shear wall behaves as area element and to model it as nonlinear model fiber hinges has to be assigned. In SAP 2000 V19.2.1 fiber hinge cannot be provided for shear wall to account for nonlinearity. Hence the nonlinearity to shear wall is assigned to concrete and steel. The shear wall is modeled as element layered with nonlinear material (concrete and steel). The concrete is assigned as unconfined concrete and steel chosen is double layer reinforcement with in plane elements as nonlinear and out of plane element as linear. The rebar size of 10 mm diameter spacing of 0.4m and cover of 0.03m is provided. The shear wall is provided for the entire bay and entire height in all four corners of the building. The base condition adopted is flexible base following Modified Winkler method. The Plan of Bare frame and Bare frame with shear wall provided at all four corners is given in Fig.2.1 and Fig.2.2

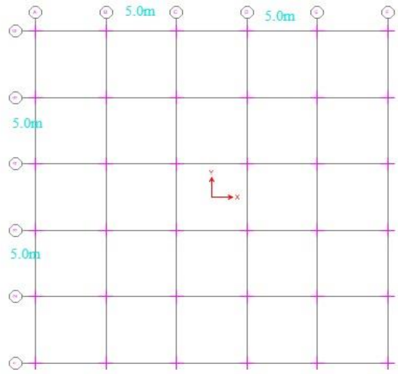

Fig.2.1 Plan of Bare frame

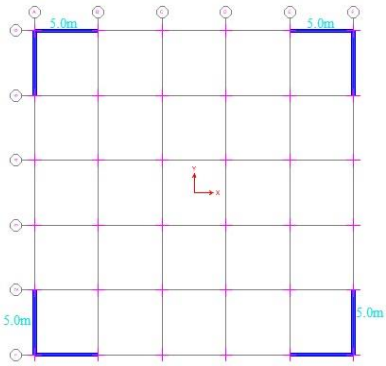

Fig.2.2 Bare frame with shear wall –corners

III. MODEL DESCRIPTION

3.1 Defining Problem: A 10 storey, 3D building with flexible soil base idealized by Modified Winkler method is modeled. The shear wall is provided at all four corners of the building. The nonlinearity is assigned to shear wall by layered sections with different types of elements such as (membrane, plate and shell elements with unconfined concrete and reinforcement.) The reinforcement is assigned nonlinear property. The analysis is performed on bare frame and bare frame with shear wall (where shear wall is provided with different element types with layered section).

3.2 Modified Winkler method: The bottom of the model is assigned flexible base where the soil is idealized by modified Winkler method. The stiffness at the base is calculated based on the formula given in ASCE41-13. The stiffness is calculated for bare frame and also for bare frame with shear wall provided at four corners of the building. Table 3.1 shows the details of stiffness formula and Fig.3.1 shows representation of MWM for bare frame and bare frame with shear wall.

3.3 Shear wall: The shear wall modeled as layer section (with materials like concrete and steel with varying number of layers) The element are discritized into finite element of size 0.5m and each node is assigned plate constraints in z direction. Table 3.2 shows the details about parameters taken for shear wall. The building is analyzed for bare frame with flexible base, later the building is modeled as membrane element, plate element and shell element with 3 layers and 5 layers and also for combination of membrane and plate element with 10 layers.

Table 3.1. Stiffness formula for MWM calculation

Sl	Degree of freedom	Stiffness	Stiffness of foundation at surface	Embedment factor
1	Translation along X-axis	K_x=Kx$_{sur}$ x β_x	Kxsur= GB/(2-γ)*(3.4*(L/B)^0.65+1.2)	βx=[1+0.21*SQRT(D/B)]*[1+1.6*(Dd[B+L]/BL2)^0.4]
2	Translation along Y-axis	Ky=Ky$_{sur}$ x β_y	Kysur=(GB/(2-γ))*(3.4*(L/B)^0.65+0.4*(L/B)+0.8)	βy=[1+0.21*SQRT(D/L)]*[1+1.6*[hd[B+L]/LB2]^0.4]
3	Translation along Z-axis	Kz=Kz$_{sur}$ x βz	Kz$_{sur}$= (GB/(1-γ))*(1.55*(L/B)^$^{0.75}$+0.8)	βz=((1+(1/21*D/B)*(2+2.6B/L))*(1+0.32*(d(B+L)/BL)^$^{2/3}$)
4	Rocking about X-axis	$K\theta_{xx}$= $K\theta_{xx}$*$\beta\theta_x$	$K_{\theta xx}$=(GB^3/(1-γ))*(0.4(L/B)+0.1)	$\beta_{\theta x}$=1+2.5(d/B)*[1+2d/B*[d/D]^$^{-0.2*}$ SQRT(B/L)]
5	Rocking about Y-axis	$K\theta_{yy}$= $K\theta_{yy}$*$\beta\theta_y$	$K_{\theta yy}$=(GB^3/(1-γ))*(0.47*(L/B)^$^{2.4}$+0.034)	$\beta_{\theta x}$=1+1.4*(d/L)^$^{0.6*}$[1.5+3.7*(d/L)^$^{1.9*}$(d/D)^$^{-0.6}$]
6	Rocking about Z-axis	$K\theta_{zz}$= $K\theta_{zz}$*$\beta\theta_z$	$K_{\theta zz}$=GB^{3*}(0.53*(L/B)$^{2.45}$+0.51)	βzz= 1+2.6(1+(B/L))(d/B)^$^{0.9}$

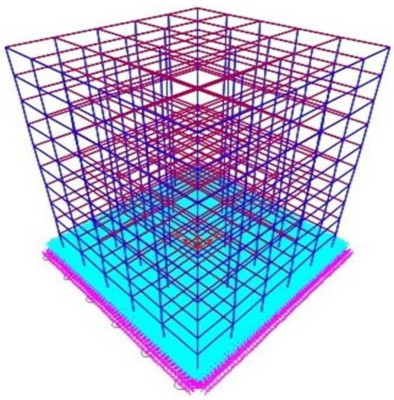

Fig.3.1 Bare frame

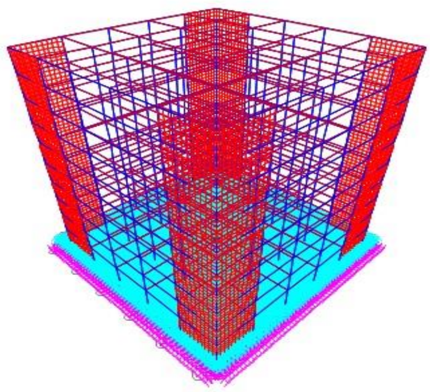

Fig.3.2 Bare frame with shear wall

Table 3.2. Shear wall parameters

Description	Thickness in m	Concrete	Reinforcement	Bar dia	Spacing in m
Shear wall corner(x, y dir)	0.12 0.5m FE Plate constraints Z dir	Unconfined Meander Elastic Isotropic	Parametric Elastic Uniaxial 2 Layer	10	0.4 cover 0.03
			In plane -S22 Non linear Out plane -Linear		

IV. RESULT AND DISCUSSION

The results obtained for bare frame and bare frame with shear wall for flexible base -MWM is discussed below:

4.1 Capacity curve: The capacity curve represented with displacement in 'm' on X axis and Base force in 'kN ' on Y axis is shown for Bare frame in Fig.4.1and Bare frame with shear wall provided at all four corner in Fig.4.2.

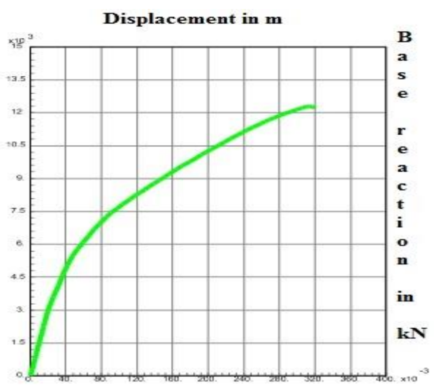

Fig.4.1 Bare Frame

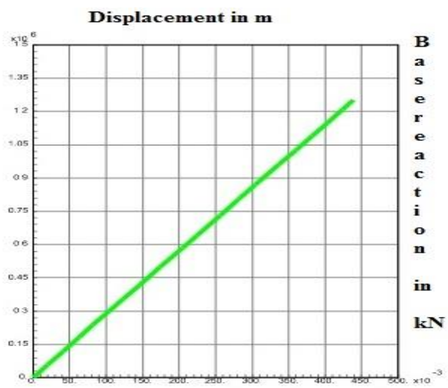

Fig.4.2 Bare frame with shear wall

The capacity curve for bare frame is compared with bare frame provided with shear wall (with different element type and layered section). As observed the Figure4.1the capacity curve has reached a maximum base force and gradually drops down whereas the Fig.4.2 shows the shape of the curve turns to be linear without any bend indicating the increase in stiffness of the building. From the above comparison one can say that the capacity curve increases the stiffness of the building after providing shear wall.

4.2 Pushover Capacity values: The Table 4.1 to Table 4.3 shows the values of capacity of the building for Bare Frame and Bare Frame with shear wall (where shear wall is provided with unconfined concrete and reinforcement for various elements(plate element, memebrane element and shell element) with reinforcement assigned nonlinear behaviour for single or double layer). The values indicate displacement, base force and number of hinges formed at various failure states.

4.2.1 For Bare frame: As observed in the Table 4.1 the base force is (7817kN) and displacement is (0.104m). Once the shear wall is provided at all four corners of the building, the base force increases and displacement decreases compared to bare frame.

4.2.2. At B- IO state: As observed in Table 4.1 the results of Bare frame-with Shell element -3 Layer, Bare frame-Shell element -5 Layer and Bare frame-with combination of (Membrane & Plate element)-10 Layer shows same displacement (0.041m) whereas the base force is 192876.51kN which is maximum in Bare frame for combination of elements (Membrane & Plate)-10 layers

Table:4.1 Pushover Capacity values for Bare frame and Bare frame with Shear wall at B-IO state

Description	*Step*	*Displacement 'm'*	*Base Force 'kN'*	*A B*	*B IO*	*IO LS*	*LS CP*	*C P C*	*C D*	*D E*	*Beyond E*	*Total*
BF-MWM	19	0.104	7817.69	1412	508	0	0	0	0	0	0	1920
BF-MWM(Membrane & Plate)-10 Layer	2	0.041	192876.51	1432	488	0	0	0	0	0	0	1920
BF-MWM(Membrane)-5 Layer	2	0.040	133211.53	1432	488	0	0	0	0	0	0	1920
BF-MWM(Plate)-5 Layer	3	0.062	179966.90	1326	594	0	0	0	0	0	0	1920
BF-MWM(Shell)-5 Layer	2	0.040	162161.00	1434	486	0	0	0	0	0	0	1920
BF-MWM(Membrane)-3 Layer	3	0.061	175678.10	1334	586	0	0	0	0	0	0	1920
BF-MWM(Plate)-3 Layer	3	0.062	134988.91	1324	596	0	0	0	0	0	0	1920
BF-MWM(Shell)-3 Layer	2	0.040	161229.63	1434	486	0	0	0	0	0	0	1920

4.2.2. At IO-LS state:

*A*t this state, In case of bare frame, the Base force is 8786kN and the displacement is around 0.139m. Providing shear wall shows that in case of Bare frame-with Shell element -3 Layer, Bare frame-Shell element -5 Layer and Bare frame-with combination of (Membrane & Plate element)-10 Layer shows same displacement (0.082m) whereas the base force is 394956.05kN which is maximum in Bare frame for combination of elements (Membrane & Plate)-10 layers

Table:4.2 Pushover Capacity values for Bare frame and Bare frame with Shear wall at IO-LS state

Description	*Step*	*Displacement 'm'*	*BaseForce 'kN'*	*A B*	*B IO*	*IO LS*	*LS CP*	*C P C*	*C D*	*D E*	*Beyond E*	*Total*
BF-MWM	25	0.139	8786.45	1378	508	34	0	0	0	0	0	1920
BF-MWM(Membrane & Plate)-10 Layer	4	0.084	394956.05	1258	638	24	0	0	0	0	0	1920
BF-MWM(Membrane)-5 Layer	4	0.082	264731.34	1258	638	24	0	0	0	0	0	1920
BF-MWM(Plate)-5 Layer	4	0.082	238205.77	1258	642	20	0	0	0	0	0	1920
BF-MWM(Shell)-5 Layer	4	0.082	326080.92	1258	638	24	0	0	0	0	0	1920
BF-MWM(Membrane)-3 Layer	4	0.083	236354.57	1252	648	20	0	0	0	0	0	1920
BF-MWM(Plate)-3 Layer	4	0.082	177937.49	1258	644	18	0	0	0	0	0	1920
BF-MWM(Shell)-3 Layer	4	0.082	323825.18	1258	638	24	0	0	0	0	0	1920

4.2.3. Comparison of the results of shear wall provided with different element types at IO-LS state:

1. In case of combination of both membrane and plate elements with ten layers: The reinforcement is provided in both directions (at top and bottom) along with unconfined concrete. The results show a displacement of 0.084m and base force of 394956kN. The results are greater compared to bare frame and other elements provided.

2. Only membrane element with 5 layers: With unconfined concrete and reinforcement provided in both direction (at top and bottom) shows lesser displacement of 0.082m and base force of 264731kN. This value is lesser than combination of both (membrane and plate) elements as discussed above.
3. Only plate elements with 5 layers: With unconfined concrete and reinforcement provided in both direction (at top and bottom) shows, lesser displacement of 0.082m and base force of 238205.77kN. This shows lesser value compared to combination of both (membrane and plate elements) as well as only membrane elements provided with 5 layers.
4. Only shell elements with 5 layers: With unconfined concrete and reinforcement provided in both direction (at top and bottom) shows, lesser displacement of 0.082m and base force of 326080.92 kN which is nearing to combination of (membrane and plate) element and greater than only membrane and only plate elements provided with 5 layers.

This shows that shell element with 5layer is almost nearing to combination of both (membrane and plate element) provided with 10 layers compared to only membrane element and plate element. Hence this shows that there is not much difference in providing only shell elements or combination of both (membrane and plate) elements.

5. Only membrane elements -3 layers: With unconfined concrete and with reinforcement provided in only one direction (at top & bottom) shows less displacement of 0.082m and base force of 236354kN which is lesser than all the above 10 layer and 5 layer elements provided.
6. Only plate elements -3 layers: With unconfined concrete and with reinforcement provided in only one direction (at top & bottom) shows lesser displacement of 0.082m and lesser base force of 177937kN. The base force is lesser than 10 layer and 5 layer elements provided individually in both direction as well as lesser than 3 layer only membrane element provided in one direction.
7. Only shell elements-3 layers: With unconfined concrete and with reinforcement provided in only one direction at top & bottom shows less displacement of 0.082m and base force of 323825kN. This value is nearing to combination of both (membrane and plate) element and shell element-5 layer with reinforcement provided in both direction. Also it is greater than only membrane-3layer and plate element-3 layer with reinforcement provided in one direction.

The above observation and discussion shows that shell element -3 layers with reinforcement provided in one direction is almost nearing to shell element -5 layers with reinforcement provided in 2 directions. Hence there is not much difference in providing shell element with reinforcement provided in one direction or both directions.

Overall observation indicates that we can choose shell element with reinforcement provided in one direction or both direction as well as combination of both (membrane and plate) element provided in both direction. However greater base force with less displacement is observed in combination of both (membrane and plate) element with reinforcement provided in both direction. Hence looking at results one can say that shear wall with unconfined concrete and combination of both (membrane and plate) element with reinforcement in both direction - 10 layer can be chosen compared to other elements considered individually with different layers.

4.2.4. At LS-CP state: at this state, In case of bare frame, the Base force is 9196.73kN and the displacement is around 0.155m. Providing shear wall shows that in case of Bare frame-with Shell element -3 Layer, Bare frame-Shell element -5 Layer and Bare frame-with combination of (Membrane & Plate element)-10 Layer shows same displacement (0.0105m) whereas the base force is 494476.11kN which is maximum in Bare frame for combination of elements (Membrane & Plate)-10 layers

Table:4.3 Pushover Capacity values for Bare frame and Bare frame with Shear wall at LS-CP state

Description	*Step*	*Displacement 'm'*	*Base Force 'kN'*	*A B*	*B IO*	*IO LS*	*LS CP*	*CP C*	*C D*	*D E*	*Beyond E*	*Total*
BF-MWM	28	0.155	9196.727	1376	508	16	20	0	0	0	0	1920
BF-MWM(Membrane & Plate)-10 Layer	5	0.105	494476.11	1200	696	6	6	0	12	0	0	1920
BF-MWM(Membrane)-5 Layer	5	0.103	331587.30	1208	688	8	8	0	8	0	0	1920
BF-MWM(Plate)-5 Layer	5	0.103	298058.42	1222	674	10	14	0	0	0	0	1920
BF-MWM(Shell)-5 Layer	5	0.103	408164.50	1206	690	8	8	0	8	0	0	1920
BF-MWM(Membrane)-3 Layer	5	0.104	297600.48	1226	670	8	16	0	0	0	0	1920
BF-MWM(Plate)-3 Layer	5	0.103	222926.88	1220	676	12	12	0	0	0	0	1920
BF-MWM(Shell)-3 Layer	5	0.103	405382.33	1206	690	8	8	0	8	0	0	1920

4.2.5 Deformed shape of building iIn case of Bare frame:

Fig.4.1 shows the deformed shape of bare frame with hinges at base in IO-LS state (step 25). Similarly Fig.4.3 shows deformed shape of building at last step of analysis with hinges at base in C-D state indicated by yellow colour.

4.2.6 Deformed shape of building iIn case of Bare frame with shear wall:

Providing shear wall at corner, combination of (membrane and plate element- 10layer) shown in Fig.4.2 at step 4, the number of hinges at base gets minimized in IO-LS state indicated by blue colour. Similarly the Fig.4.4 shows at step 18 the number of hinges is found to be less at base in C-D state indicated by yellow colour. This shows by providing shear wall at corner the number of hinges reduces at various failure states.

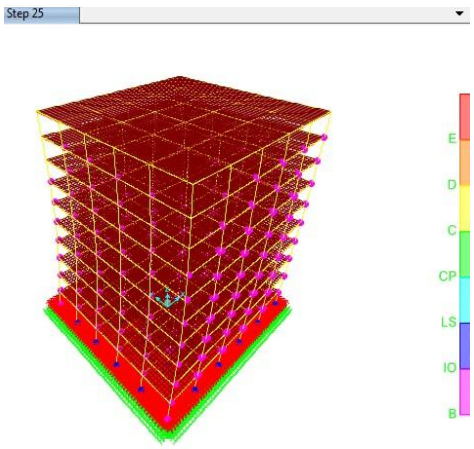

Fig. 4.1 Bare frame

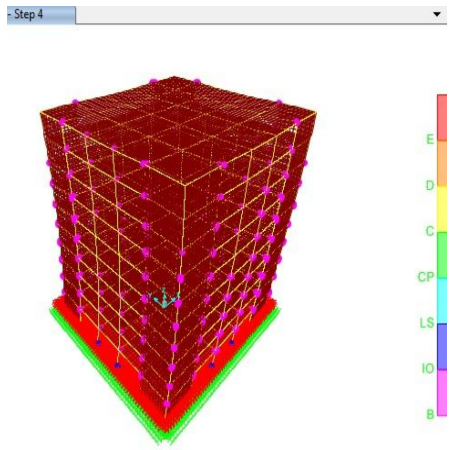

Fig. 4.2 Bare frame with shear wall

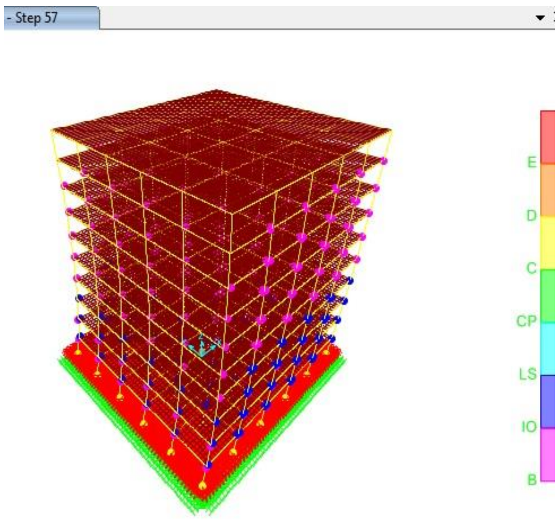

Fig.4.3 Bare frame

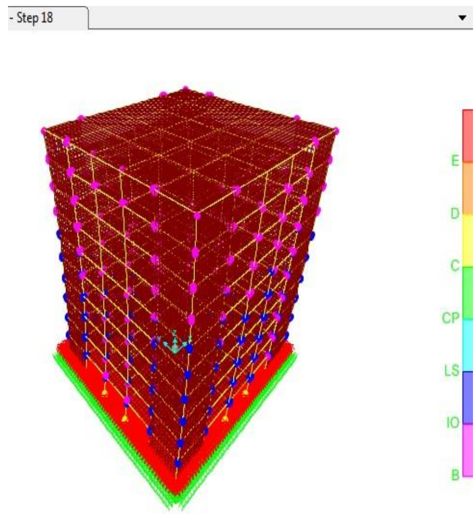

Fig.4.4 Bare frame with shear wall

V. CONCLUSION

The results obtained by performing nonlinear analysis are thoroughly studied. The analysis of a 3D building with flexible soil base performed on bare frame and bare frame with shear wall provided at all four corners of the building (for different element types and different number of layers considered) shows that :

1. Bare frame shows greater displacement with less load carrying capacity. This may be due to soil flexibility considered which displaces the building more.
2. Bare frame with shear wall shows lesser displacement and greater base force. This may be because the shear wall is provided at all four corners of the building which adds to the stiffness of the building.
3. Among layered section with different elements considered for shear wall, the shell element provided for single layer and double layer of reinforcement shows better results compared to only membrane and only plate elements.
4. It is noticed that the combination of both membrane and plate element with reinforcement provided in both direction shows better results compared to shell, membrane and plate elements provided individually.
5. The combination of membrane and plate element results is almost same as shell element with reinforcement provided in both directions. This

shows the combination of both membrane and plate element behaves same as shell element.

6. The capacity curve shows change in shape of curve to linear and stiff curve without drop indicating that the stiffness of the building increases by providing shear wall.
7. The deformed shape of the building denoted by different colour of hinges shows that the number of hinges at base gets minimized by providing shear wall at four corners compared to bare frame alone.

Overall observation shows that, the investigation is helpful to know that the shell type of element and combination of membrane and plate element with double layer reinforcement can be chosen to model shear wall. The results obtained also indicate various failure states and gives the values of displacement and base force at life safety state. The study is useful in predicting the load at collapse and also the load where the building is safe to occupy.

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