Pushover Analysis of Steel Structures with Different Plan Configuration

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Abstract— Steel is by far most useful material in construction and played an important role in last few decades. It must necessary to analyze and design a structure to perform well under seismic loads and also endow with well strength, stability and ductility for seismic design. The seismic performance of a multi-story steel frame structure is analyzed according to the provision of current Indian code (IS 800-2007), seismic data and seismic factor from Indian code (IS1893-2016). Few guidelines like Applied Technology Council (ATC40) and Federal Emergency Management Agency (FEMA356) have used. The study of Steel Structures with different plan configuration is very essential now a day, as it will help to understand the behaviour of the structure in certain circumstances. In this study typical G+4 story Steel frame buildings have been analyzed, for different plan configuration in one direction i.e. in X- direction. In this work different models were prepared with different span length of frame and Performance of each frame is studied through pushover analysis. In the present study, four different types of model analyzed using pushover analysis in x & y direction respectively. The pushover analysis has been carried out using Etabs v18, a product of computer and structure international. The results of all models are analyze and compare in term of base shear, story displacement, pushover curve, spectrum curve, performance point of the structure and story drift.

Keywords: Pushover analysis, Base shear, performance point, displacement, drift, Etabs

I. INTRODUCTION

EARTHQUAKE can cause greatest damages to humanity among all the natural hazards. Since earthquake forces are unpredictable and random in nature, proper analysis of the structures must be ensured to withstand such loads. The recent developments in the performance-based engineering design have brought the non-linear static (NSP) or pushover analysis to the forefront. It has replaced the conventional analysis procedures due to its simplicity and proved to be a useful and effective tool for assessing the real strength of structures. Pushover analysis can be either force controlled or displacement controlled. The pushover analysis can provide significant perception and understanding about the weak links in the structure. Etabs V18 can perform static or dynamic, linear or nonlinear analysis of structural systems. To perform pushover analyses in Etabs V18, users can create and apply hinge properties. Etabs V18 is fully equipped with US, Canadian and International Design standards and codes like ACI concrete code, AISC building codes and AASHTO specifications. These integrated design code features can easily generate wind, wave and seismic loads with comprehensive automatic steel and concrete design checks. Pushover analysis is a static non-linear technique in which the magnitude of the structural loading is incremented in the lateral direction of the structure according to a certain pre-defined pattern. Generally, it is assumed that the behaviour of the structure is controlled by its fundamental mode and the predefined pattern is expressed in terms of either story shear or fundamental mode shape. FEMA-273 and its successor FEMA-356 describe about the non-linear static procedure (NSP) or pushover analysis and its uses in the structural engineering field. It is recommended as a standard tool for estimating seismic demands for buildings. In Etabs V18, a frame element is modelled as a line element having linearly elastic properties and nonlinear force-displacement characteristics of individual frame elements are modelled as hinges represented by a series of straight line segments. There are three types of hinge properties in Etabs V18. They are default hinge properties, user-defined hinge properties and generated hinge properties. Studies show that user defined hinge model gives better results than default hinge model. Moment-curvature relationship is used to model plastic hinge behaviour in non-linear analysis. The seismic performance of a structure can be evaluated in terms of pushover curve, plastic hinge formation etc. The maximum base shear capacity of structure can be obtained from base shear versus roof displacement curve.

II. NON-LINEAR STATIC ANALYSIS (PUSHOVER METHOD)

In elastic analysis, there were procedures for the seismic evaluation and design of upgrades of structure as well as design of new construction. The generic process of inelastic analysis is similar to conventional linear procedure in that the engineer develops a model of the structure in which is then subjected to a representation of the anticipated seismic ground motion. The coefficient method is fundamentally a displacement modification procedure that is presented in FEMA -356. The coefficient method of displacement modification from FEMA- 356: - The coefficient method is the primary non-linear static procedure presented in FEMA-356. This approach modifies the linear elastic response of the equivalent SDOF system.

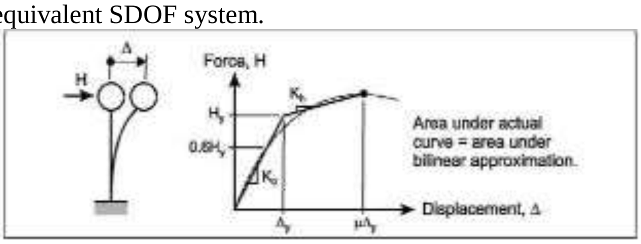


Fig. 1: Bilinear approximation of push-over curve

The peak elastic spectral displacement is directly related to the spectral acceleration by the relation.

Sd= (Teff) 2/4π2xSa

Where, Sd = spectral displacement. Sa = spectral acceleration. Teff = effective time period depends upon the relative stiffness of structure.

The NSP may be used for any structure and any Rehabilitation Objective, with the following exceptions and limitations. • The NSP should not be used for structures in which higher mode effects are significant, unless an LDP evaluation is also performed. To determine if higher modes are significant, a modal response spectrum analysis should be performed for the structure using sufficient modes to capture 90% mass participation, and a second response spectrum analysis should be performed considering only the first mode participation. Higher mode effects should be considered significant if the shear in any story calculated from the modal analysis considering all modes required obtaining 90% mass participation exceeds 130% of the corresponding story shear resulting from the analysis considering only the first mode response. When an LDP is performed to supplement an NSP for a structure with significant higher mode effects, the acceptance criteria values for deformation controlled actions (m values).

This method aims to produce structures with predictable seismic performance. The three key elements of this method are:

1) Capacity: It is a representation of the structures ability to resist the seismic demand.
2) Demand: It is a representation of the earthquake ground motion.
3) Performance: It is an intersection point of capacity spectrum and demand spectrum.

The performances levels as per FEMA, ATC 40 are:

- Immediate occupancy IO: damage is relatively limited; the structure retains a significant portion of its original stiffness and most if not all its strength.
- Life safety LS: substantial damage has occurred to the structure, and it may have lost a significant amount of its original stiffness. However, a substantial margin remains for additional lateral deformation before collapse would occur.
- Collapse prevention CP: at this level the building has experienced extreme damage, if laterally deformed beyond this point; the structure can experience instability and collapse.

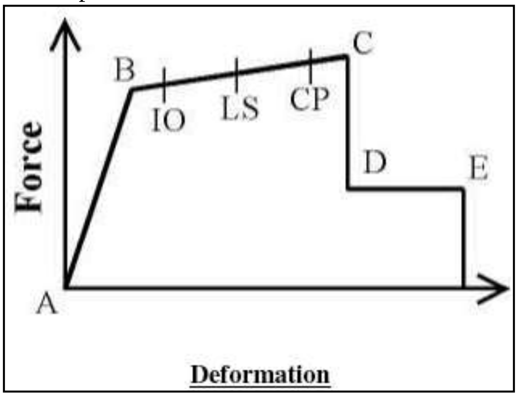


Fig. 2: Deformation

Nonlinear static analysis may be classified as displacement control when lateral displacement is compulsory on the structure and its equilibrium determine the forces. Likewise, when lateral forces are obligatory, the study is termed as force-controlled pushover analysis. The importance of the target force and target displacement is to calculate the maximum displacement or maximum force expected to be experienced by the building structure throughout the design earthquake. Response of structure clear of maximum strength can be determined only by displacement controlled pushover analysis. Hence, in the present study, displacement controlled pushover method is used for analysis of building structural steel frames with and without bracings.

This paper includes the structural behaviour of steel building with different plan configuration under lateral and static loading. The main aspire of study has been to recognize the behaviour of such arrangement which causes minimum displacement such contributes to greater lateral stiffness to the building. This process aims to produce structures with predictable seismic performance. The three key elements of this method are: -

- Capacity: - It is a representation of the structures ability to resist the seismic demand.
- Demand: - It is a representation of the earthquake ground motion.
- Performance: - It is an intersection point of capacity spectrum and demand spectrum.

Different states such as Immediate Occupancy, Life Safety, Collapse prevention and collapse are defines as per ATC 40 and FEMA 356.

Performance Level	Structural Performance	Non Structural Performance
Operational (O)	Very light damage No permanent drift Substantially original strength and stiffness	Negligible damage. Power & other utilities are available
Immediate Occupancy (IO)	Light damage No permanent drift Substantially original strength & stiffness minor cracking Elevators can be restarted Fire protection operable	Equipments & content secure but may not operate due to mechanical/utility failure
Life Safety (LS)	Moderate damage Some permanent drift Residual strength & stiffness in all stories Gravity elements function building may be beyond economical repair	Falling hazard mitigated but extensive systems damage
Collapse Prevention (CP)	Severe damage Large permanent drifts	Extensive damage

	Little residual strength & stiffness Gravity elements function Some exits blocked Building near collapse	

Table 1: Performance level of structure

A. Linear Dynamic analysis (Response spectrum)

Here the full design base shear and lateral force all along some principal direction is given in terms of design horizontal seismic coefficient and seismic mass of the building. Design horizontal seismic coefficient depends on the seismic zone importance factor of the structure, seismic zone factor of site, response reduction factor of the lateral load resisting elements and the fundamental period of the structure. The method usually used for the equivalent static analysis is given below:

1) *Determination of fundamental natural period (Ta) of the buildings Ta = 0.075h0.075 Moment resisting RC frame building without brick infill wall.*

Ta = 0.085h0.075 Moment resisting steel frame building without brick infill walls

Ta = 0.09h /√d All other buildings including moment resisting RC frame building with brick infill walls.

Where, h - Is the height of building in meter

d- Is the base dimension of building at plinth level in m, along the considered direction of lateral force.

2) *Determination of base shear (VB) of the building*

VB = Ah×W

Where,

Ah=(Z/2)*(I/R)*(Sa/g) is the design horizontal seismic coefficient, which depends on the seismic zone factor (Z), importance factor (I), response reduction factor (R) and the average response acceleration coefficients (Sa/g). Sa/g in turn depends on the nature of foundation soil (rock, medium or soft soil sites), natural period and the damping of the structure.

3) *Distribution of design base shear The design base shear VB thus obtained shall be distributed along the height of the building as per the following expression:*

$$Q_i = V_B \frac{W_i h_i^2}{\sum_{j=1}^{n} W_j h_j^2}$$

Where, Qi is the design lateral force, Wi is the seismic weight, hi is the height of the ith floor measured from base and n is the number of stories in the building.

B. Nonlinear Static Analysis (Pushover Analysis)

Pushover analysis is one of the methods available to understand the seismic behaviour of the structure. Nonlinear static pushover analysis was used to evaluate the seismic performance of the structures. The numerical analysis was done using SAP2000 18 and guidelines of ATC-40 and FEMA 356 were followed. The overall performance evaluation was done using capacity curves, storey displacements, base shear, spectrum curve and ductility ratios. Plastic hinge hypothesis was used to capture the nonlinear behaviour according to which plastic deformations are lumped on plastic hinges and rest of the system shows linear elastic behaviour.

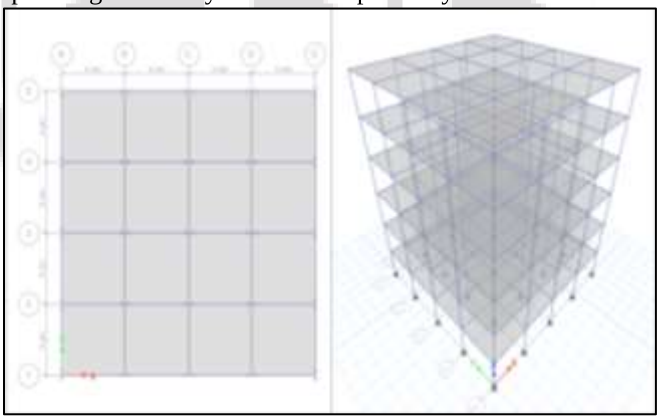
III. STRUCTURAL MODELLING

For the analysis work, four models of building (G+4) floors are made to know the realistic behaviour of building during earthquake. In these study different span in x-direction have been taken. Typically bay width is taken 4m in Y direction. No of bays in Y- directions are 4. Total height of building is 20.5 m.. Story height (floor to floor) 3.5m were considered in this study. All the joints of beam and column are rigid. There are assigned Diaphragm in all joints because; it is horizontal or nearly horizontal system which transmits lateral forces to vertical resisting system. The models were analyzed as per Indian standard code and Fema356 and ATC 40. Different arrangement of different span configuration and a bare frame considered below. All columns are fixed from base for foundation.

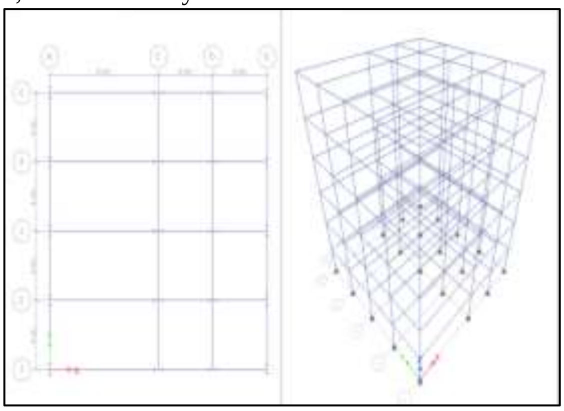
A. SPECIFICATIONS OF MODELS

Four models for G+4 storey Steel Structures of area 16 m x 16 m. have been prepared, designed and compared in zone v as per IS 1893:2016. The models with different span length in x-direction have been prepared and compared with regular bare frame model whose performance and results were studied and compared.

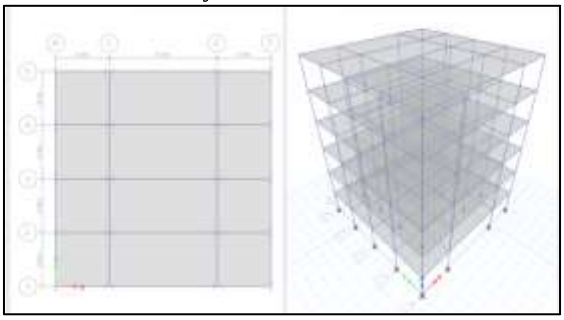
Model 1 – Regular Frame Building of 4 spans, each of 4m span length in x & y direction respectively.



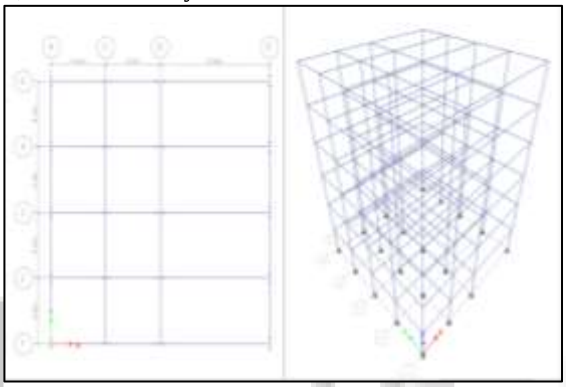
Model 2 – Steel Frame Building of 3 spans, one of 8 m. on left and others are of 4m each in x direction while having 4 spans, each of 4m in y direction.



Model 3 – Steel Frame Building of 3 spans, one of 8 m. on centre and others are of 4m each in x direction while having 4 spans, each of 4m in y direction



Model 4 – Steel Frame Building of 3 spans, one of 8 m. on right and others are of 4m each in x direction while having 4 spans, each of 4m in y direction



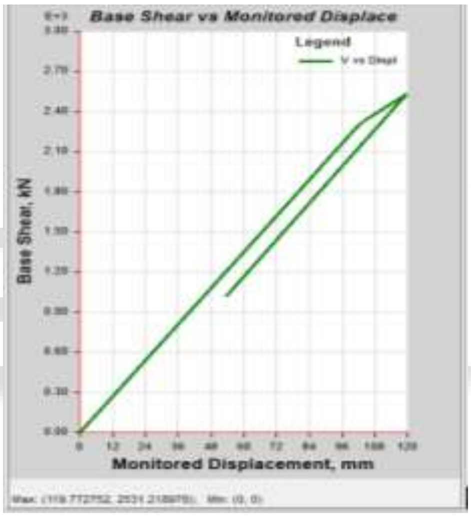
The dimensions of beams and columns have been designed according to the span length. Other data used for the purpose of analysis have been taken from IS 1893:2016

General Properties	
No. of storeys	G+4
Typical Storey Height	3.5 m.
For 4m span length:	
Size of Column	ISMB 500
Size of Beam	ISWB 500
For 8 m span length:	
Size of Column	ISMB 600
Size of Beam	ISWB 600(2)
Thickness of Slab	150 mm.
Thickness of Wall	230 mm.
Material Properties	
Grade of Concrete	M 25
Grade of Steel Section	Fe 345
Type of Loading	
Wall Load	14 KN/m
Live Load	2 KN/m^2
Floor Finishing	1.5 KN/m^2
Seismic Details (IS 1893:2016)	
Seismic Zone	V
Zone Factor	0.36
Importance Factor	1.2
Type of Soil	II - Medium
Building Type (R)	5 (SMRF)

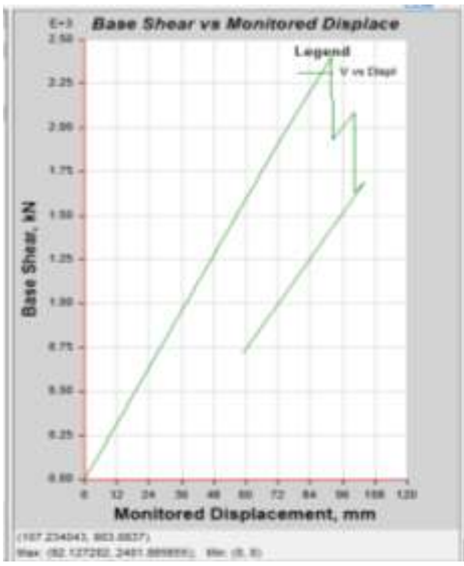
IV. Results

Procedure of pushover analysis

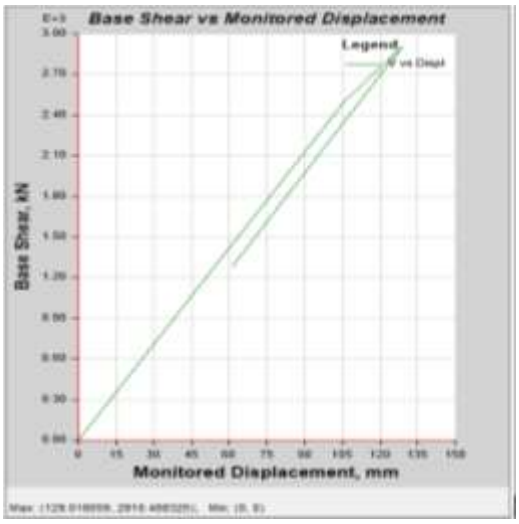
- Define all the material properties, frame sections, load cases and mass source.
- Assign hinge properties available in SAP2000 Nonlinear as per ATC-40 to the frame elements. For the beam default hinge that yields based upon the flexure (M3) and shear(V2) is assigned, for the column default hinge that yields based upon the interaction of the axial force and bending moment (P M2 M3) is assigned, and for the equivalent diagonal strut default hinge that yields based upon the axial force (P) only is assigned.
- Define three static pushover cases. In the first case gravity load is applied to the structure, in the second case lateral load.
- After defining the all load cases run the analysis for the pushover load case and nonlinear gravity load case.
- Pushover curve of all braced frame structure and bare frame structure have found after analysis. The capacity of the building is determined by pushover curve. All types of results are discussed below.



Static Pushover Curve for Model 1



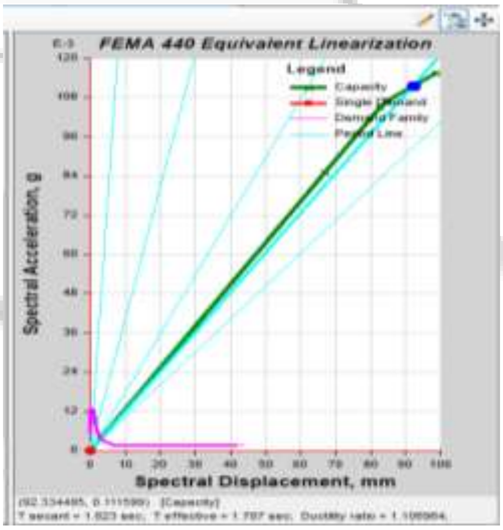
Static Pushover Curve for Model 2
Static Pushover Curve for Model 3



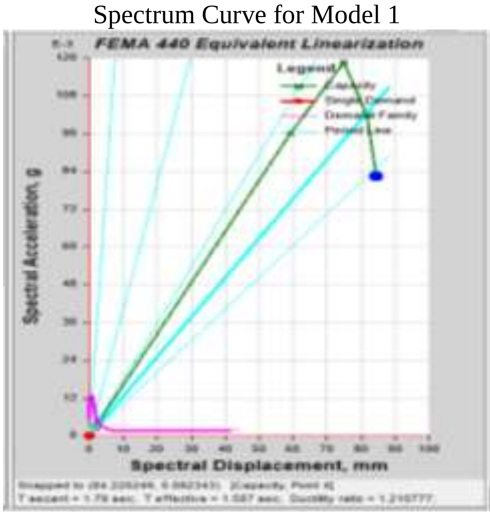
Static Pushover Curve for Model 4

In above figure pushover curves of all buildings have obtained, from the Pushover curve the data about displacement and base shear have obtained.

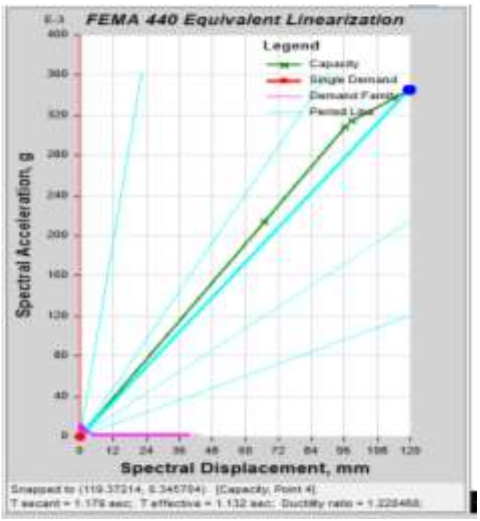
Capacity spectrum curve is useful for calculate the overall demand of the structure and capacity of the structure. It is useful to btain the performance point of the structure. Spectrum curve of all buildings are discussed below in figures.



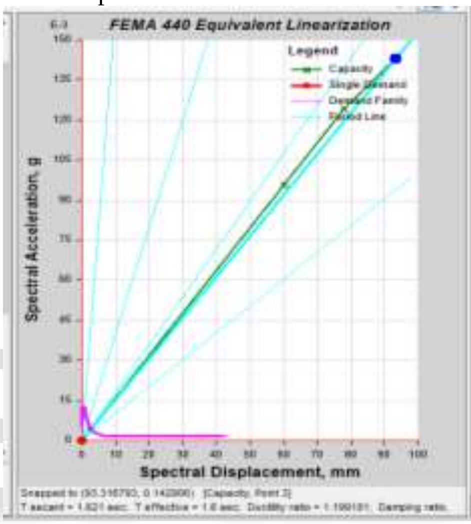
Spectrum Curve for Model 1



Spectrum Curve for Model 2



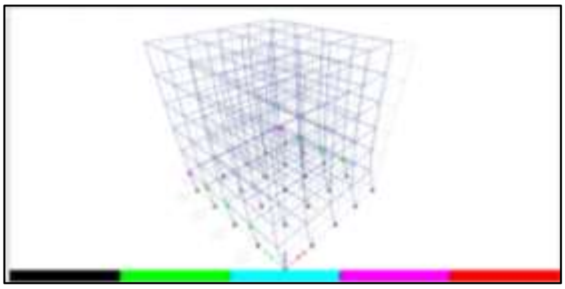
Spectrum Curve for Model 3

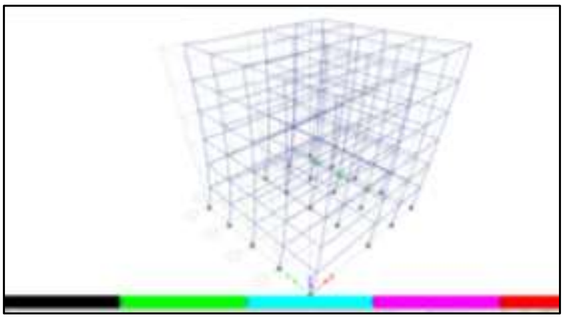


Spectrum Curve for Model 4

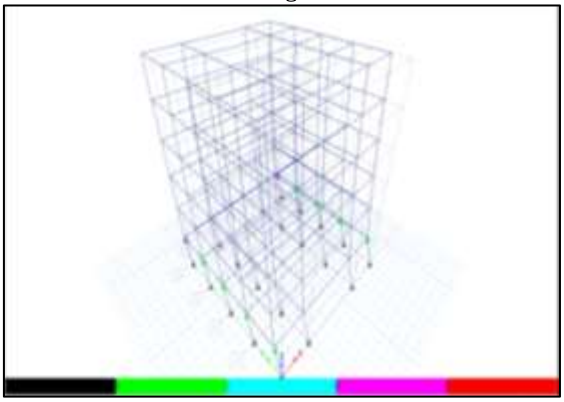
In the below figures shown that the location of plastic hinges formed for different performance levels in their final step of analysis for PUSH X & PUSH Y direction. Whenever we check the performance of the structure we calculate the deformation of the hinges.

If hinges are in O-CP (Operational to collapse prevent) stage, we can say that overall structure is safe. The various types of location and deformation of hinges are given below.

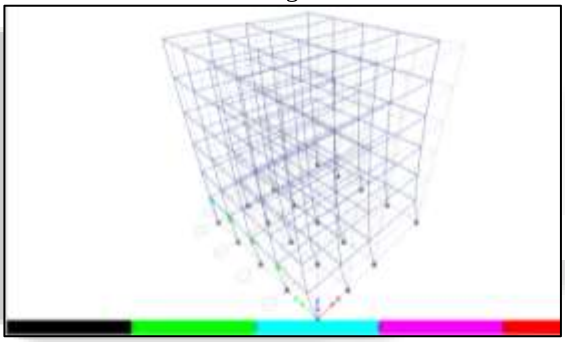

Location of hinges in Model 1



Location of hinges in Model 2

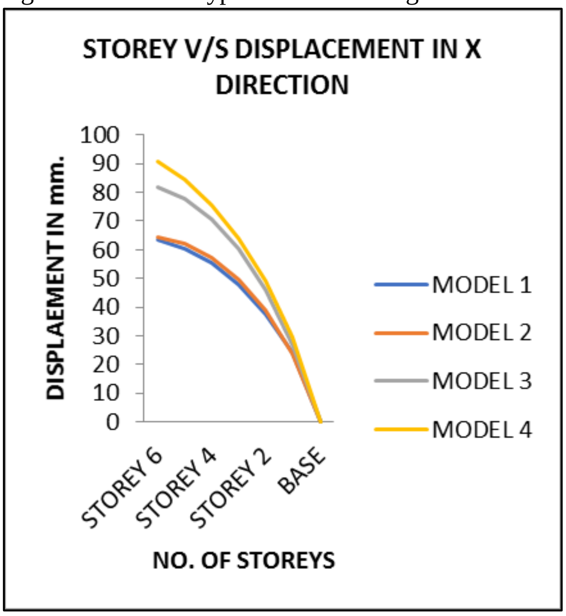


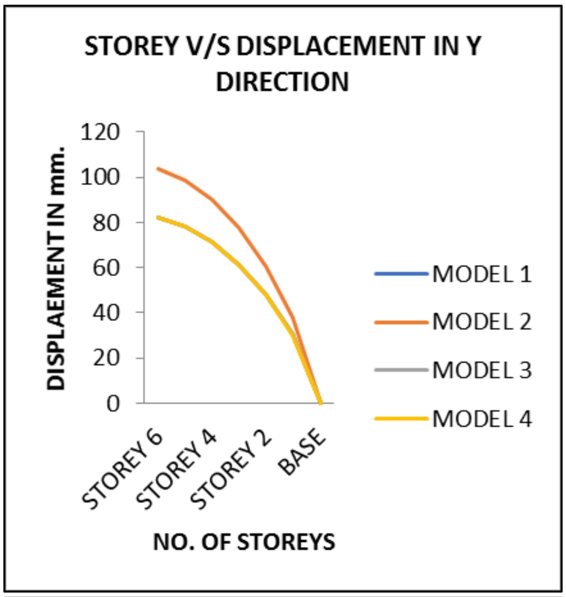
Location of hinges in Model 3

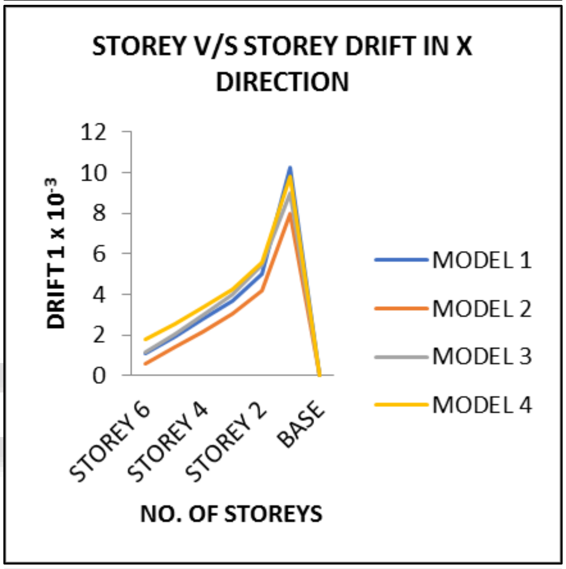


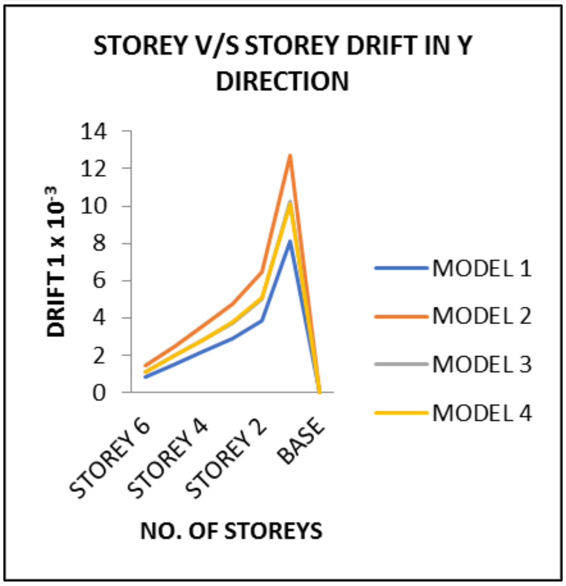
Location of hinges in Model 4

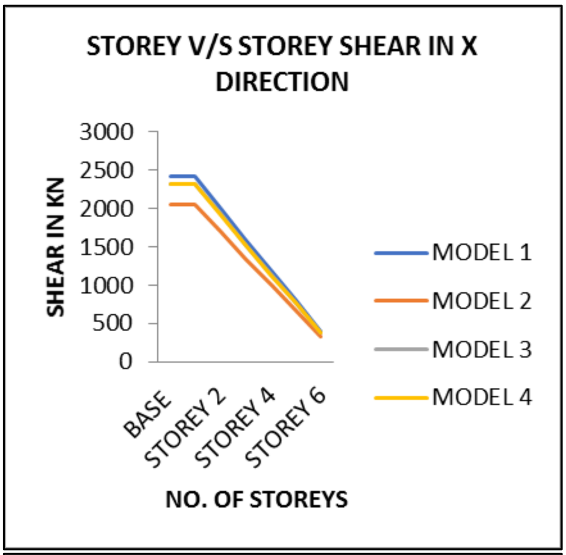
From the above results the location of different types of hinges for different types of the buildings are obtained.

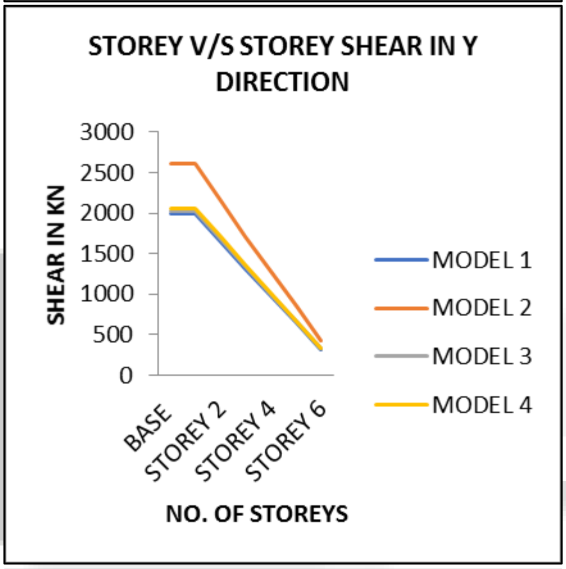


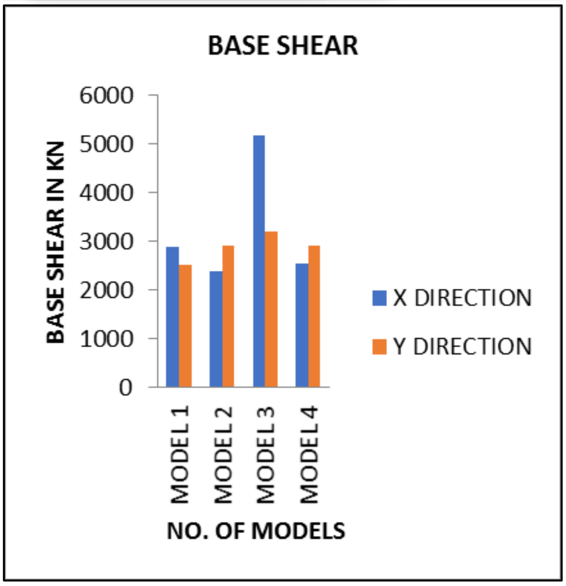












V. CONCLUSIONS:

In this thesis, various frames and structures having different configuration have been analysed to study their behaviour when subjected to lateral loads. All the frames and structures were analysed with the same method as stated in IS 1893- part 1: 2016. The results obtained for the building carried out through response spectrum approach and non linear static analysis approach i.e. Pushover Analysis and will be near to realistic response of the structure to the actual. Following conclusions are made on the basis of the study –

Following are the main conclusions are made from the present study:

1) The storey displacement in X-direction is higher for non symmetric buildings as compare to symmetric building. The value of displacement in model 4 is greater among all. It is 48% higher than the value of displacement in symmetric model i.e. model 1.
2) The storey in Y-direction which is kept symmetric in all models remains same in all models except the model 2 whose value is 25% more than the displacement value of other models.
3) The ratio of story drift is less for model 2 as compare to other models in x-direction while the ratio of drift in y-direction is less for model 1.
4) The storey shear for all models remains almost same in x-direction while in y-direction the value is higher for model 2.
5) The value of base shear is higher when the central span is of greater length as compare to others due to least lateral stiffness in x-direction while the other models have almost same values of base shear having little bit variation.
6) The performance points are determined for all five building models. All building models are safe. The hinges results of all models are in between the safe zone IO-CP.
7) Spectral acceleration in model 2, model 3 and model 4 as comparison to spectral acceleration in model 1are 72.22%, 78.78%and 89.65% respectively higher.
8) From pushover analysis carried on all models, effective damping in model 2, model 3 and model 4 are 83.91%, 85.20%and 93.82% respectively greater as compared to effective damping in model 1.

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