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Pushover Analysis of RC Structures with Infill Walls Using Equivalent Strut Approach

[1]Agaz Mirza, [2]Dr J N Vyas

[1]PG Student, [2]Professor
[1,2]Department of Civil Engineering
[1,2]Mahakal Institute of Technology & Management, Ujjain

ABSTRACT—

RC Buildings are very ordinary type of construction in India. Analytically while modelling the structure, we design only structural members which transmit the load like beams, columns, slabs and footings, where walls are not considered while designing and their impact on the structural response is neglected. Their impact is shown in the global behaviour of RC frames subjected to seismic loads. So it is very important to study the behaviour of infill on the RC bare frames. The presence of infill results in increase in the structural stiffness; it also increases natural frequency of vibration which depends on seismic spectrum. In addition to that, it also decreases the storey drift demands and increases the storey lateral forces. This study presents a pushover analysis using E-tabs for reinforced concrete (RC) frames. The main purpose is to study the effect of the infill on failure patterns of the RC frames. The Finite Element Method (FEM) model considered an RC frame with in-filled wall with its variation in thickness using equivalent strut method. The objective of this paper is to understand the performance of the building with varying structural parameters and compare performance of infill Structures with the structures without infill in different seismic zones.

Keywords: Reinforced concrete frames, Infill, Time period, Stiffness, Base shear, Pushover Analysis.

1.1 Introduction -

The RC (reinforced concrete) frame structures provided with masonry infill walls are the most common type of structures used for multi-storey constructions in many countries. In this type of structures, the exterior masonry walls and the interior partitions are considered as non-structural elements, and usually, the structural interaction between the frame and infill is ignored in the seismic design/assessment especially in the past.

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.

1.2 Infill Walls

The infill wall is the supported wall that closes the perimeter of a building constructed with a three-dimensional framework structure (generally made of steel or reinforced concrete). Therefore, the structural frame ensures the bearing function, whereas the infill wall serves to separate inner and outer space, filling up the boxes of the outer frames. The infill wall has the unique static function to bear its own weight. The infill wall is an external vertical opaque type of closure. With respect to other categories of wall, the infill wall differs from the partition that serves to separate two interior spaces, yet also non-load bearing, and from the load bearing wall. The latter performs the same functions of the infill wall, hygro-thermically and acoustically, but performs static functions too.

1.3 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.

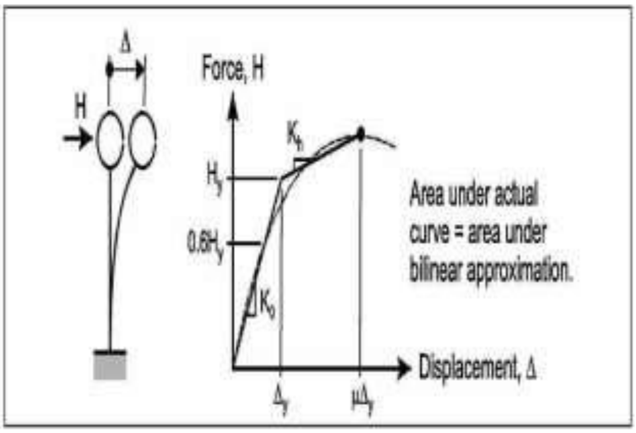


Figure: Bilinear approximation of push-over curve

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.

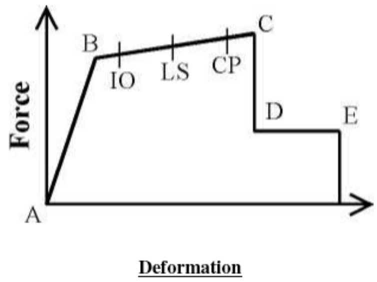


Fig. 2: Deformation

Target Displacement

The fundamental question in the execution of the pushover analysis is the magnitude of the target displacement at which seismic performance evaluation of the structure is to be performed. The target displacement serves as an estimate of the global displacement of the structure is expected to experience in a design earthquake.

Use of Pushover Results

Pushover analysis has been the preferred method for seismic performance evaluation of structures by the major rehabilitation guidelines and codes because it is conceptually and computationally simple. Pushover analysis allows tracing the sequence of yielding and failure on member and structural level as well as the progress of overall capacity curve of the structure. The expectation from pushover analysis is to estimate critical response parameters imposed on structural system and its components as close as possible to those predicted by nonlinear dynamic analysis. Pushover analysis provides information on many response characteristics that cannot be obtained from an elastic static or elastic dynamic analysis. These are;

- Estimates of inter story drifts and its distribution along the height.
- Determination of force demands on brittle members, such as axial force demands on columns, moment demands on beam-column connections.
- Determination of deformation demands for ductile members.
- Identification of location of weak points in the structure (or potential failure modes).

Pushover analysis also exposes design weaknesses that may remain hidden in an elastic analysis. These are story mechanisms, excessive deformation demands, strength irregularities and overloads on potentially brittle members.

Limitations of Pushover Analysis

Although pushover analysis has advantages over elastic analysis procedures, underlying assumptions, the accuracy of pushover predictions and limitations of current pushover procedures must be identified.

There are many unsolved issues that need to be addressed through more research and development. Examples of the important issues that need to be investigated are:

- Incorporation of torsional effects (due to mass, stiffness and strength irregularities).
- 3-D problems (orthogonality effects, direction of loading, semi-rigid diaphragms, etc)
- Use of site-specific spectra.
- Cumulative damage issues.
- Most importantly, the consideration of higher mode effects once a local mechanism has formed.

Safety Evaluation of Reinforced Concrete Buildings

Safety against collapse of reinforced concrete is usually defined in terms of its ductility ratios. The design of reinforced concrete structures is performed by using resistance smaller than the one required for the system to remain elastic under intense ground shaking. Then, the seismic codes implicitly cause structural damages during strong earthquake motions and the design relies on the capacity of the structures to undergo large inelastic deformations and to dissipate energy without collapse.

Seismic Vulnerability

The vulnerability of a building subjected to an earthquake is dependent on seismic deficiency of that building relative to a required performance objective. The seismic deficiency is defined as a condition that will prevent a building from meeting the required performance objective. Thus, a building evaluated to provide full occupancy immediately after an event may have significantly more deficiencies than the same building evaluated to prevent collapse.

Stiffness:

A building is made up of both rigid and flexible elements. For example, beams and columns may be more flexible than stiff concrete walls or panels. Less rigid building elements have a greater capacity to absorb several cycles of ground motion before failure, in contrast to stiff elements, which may fail abruptly and shatter suddenly during an earthquake. Earthquake forces automatically focus on the stiffer, rigid elements of a building.

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.

This paper includes the structural behaviour of RC building with different varying paramters. 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.

Table – 1

Performance level of structure

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

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.

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.

2. OBJECTIVE OF THE STUDY –

- To study the effect of infill walls and without infill walls on structure.
- To study the effect of infill walls with varying thickness on structure.
- To study the effect of different infill materials on structure.
- To study the effect of opening in infill walls on structure.
- To study the performance level of the structure.
- The considered objectives are useful to study the overall behaviour of the structure under the seismic load, from which the performance level can be determined.

3. STRUCTURAL MODELLING

Three models for G+3 storey RC Structure of area 8 m x 8 m. have been prepared, designed and compared in zone IV as per IS 1893:2016. The models with different infill properties have been prepared and compared with regular bare frame model whose performance and results were studied and compared.

Details of Models:

Model 1 – Regular Frame Building without infill walls of 2 spans, each of 4m span length in x & y direction respectively.

Model 2 – Regular Frame Building with infill walls (brick) of thickness 110 mm of 2 spans, each of 4m span length in x & y direction respectively without opening.

Model 3 – Regular Frame Building with infill walls (brick) of thickness 110 mm of 2 spans, each of 4m span length in x & y direction respectively with 25% opening.

Model 4 – Regular Frame Building with infill walls (brick) of thickness 110 mm of 2 spans, each of 4m span length in x & y direction respectively with 50% opening.

Model 5 – Regular Frame Building with infill walls (brick) of thickness 200 mm of 2 spans, each of 4m span length in x & y direction respectively without opening.

Model 6 – Regular Frame Building with infill walls (brick) of thickness 200 mm of 2 spans, each of 4m span length in x & y direction respectively with 25% opening.

Model 7 – Regular Frame Building with infill walls (brick) of thickness 200 mm of 2 spans, each of 4m span length in x & y direction respectively with 50% opening.

Model 8 – Regular Frame Building with infill walls (fly ash brick) of thickness 110 mm of 2 spans, each of 4m span length in x & y direction respectively without opening.

Model 9 – Regular Frame Building with infill walls (fly ash brick) of thickness 110 mm of 2 spans, each of 4m span length in x & y direction respectively with 25% opening.

Model 10 – Regular Frame Building with infill walls (fly ash brick) of thickness 110 mm of 2 spans, each of 4m span length in x & y direction respectively with 50% opening.

Model 11 – Regular Frame Building with infill walls (fly ash brick) of thickness 200 mm of 2 spans, each of 4m span length in x & y direction respectively without opening.

Model 12 – Regular Frame Building with infill walls (fly ash brick) of thickness 200 mm of 2 spans, each of 4m span length in x & y direction respectively with 25% opening.

Model 13 – Regular Frame Building with infill walls (fly ash brick) of thickness 200 mm of 2 spans, each of 4m span length in x & y direction respectively with 50% opening.

Model 14 – Regular Frame Building with infill walls (concrete blocks) of thickness 110 mm of 2 spans, each of 4m span length in x & y direction respectively without opening.

Model 15 – Regular Frame Building with infill walls (concrete blocks) of thickness 110 mm of 2 spans, each of 4m span length in x & y direction respectively with 25% opening.

Model 16 – Regular Frame Building with infill walls (concrete blocks) of thickness 110 mm of 2 spans, each of 4m span length in x & y direction respectively with 50% opening.

Model 17 – Regular Frame Building with infill walls (concrete blocks) of thickness 200 mm of 2 spans, each of 4m span length in x & y direction respectively without opening.

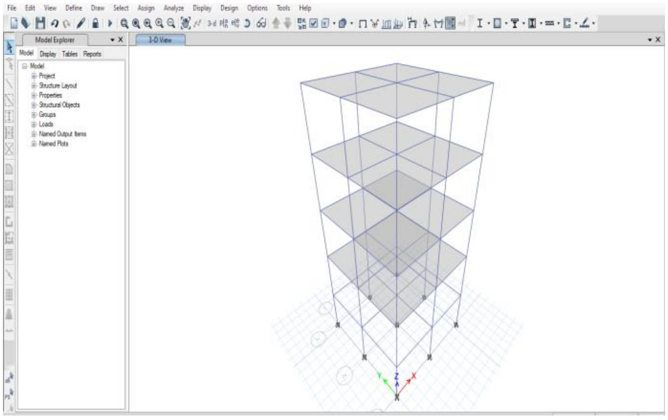
Model 18 – Regular Frame Building with infill walls (concrete blocks) of thickness 200 mm of 2 spans, each of 4m span length in x & y direction respectively with 25% opening.

Model 19 – Regular Frame Building with infill walls (concrete blocks) of thickness 200 mm of 2 spans, each of 4m span length in x & y direction respectively with 50% opening.

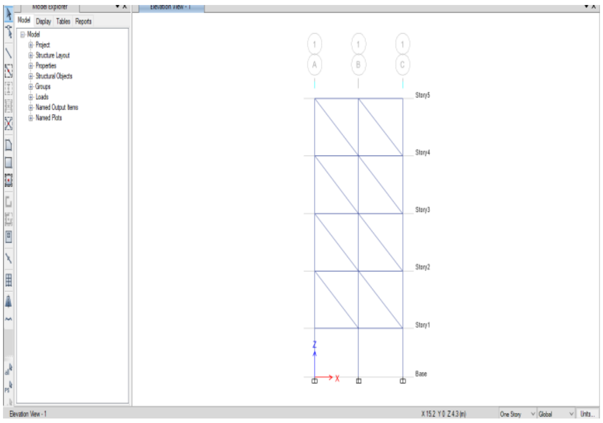
The dimensions of beams and columns have been designed according to the span length. Other data used for the purpose of analysis have been taken from IS 1893:2016

General Properties	
No. of storeys	G+3
Typical Storey Height	3.5 m.
For 4m span length:	
Size of Column	300 x 450
Size of Beam	300 x 400
Thickness of Slab	150 mm.
Thickness of Wall	110 mm, 200 mm
Material Properties	
Grade of Concrete	M 20
Grade of Steel	Fe500

For Infilled walls (clay brick)	Unit Weight = 16 KN/m3
For Infilled walls (fly ash brick)	Unit Weight = 18 KN/m3
For Infilled walls (concrete blocks)	Unit Weight = 18 KN/m3
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	IV
Zone Factor	0.24
Importance Factor	1.2
Type of Soil	II - Medium
Building Type (R)	3 (OMRF)



BUILDING WITHOUT INFILL WALLS



BUILDING WITH INFILL WALLS

Equivalent Strut Method

Width of Strut –

$$w = 0.175\,(\alpha)^{-0.4} L$$

Where, w = width of strut

α = Stiffness factor

L = Diagonal Length of Strut

Stiffness factor α can be given by –

$$\alpha = h\{(\frac{E_m t \sin 2\theta}{4 E_f I_c h})^{\frac{1}{4}}\}$$

Where E_m – Modulus of Elasticity for Masonry – 550 f_m

& f_m – Compressive Strength of Masonry

t – Thickness of Infill Wall

θ - Angle of Inclination – (Clear Height between Beams / Clear Distance between Columns)

E_f – Modulus of Elasticity for Concrete – 5000 $\sqrt{f_{ck}}$

I_c – Moment of Inertia of Columns

h = Clear Height between Beam of Adjacent Floors

For This Study, Percentage of Reduction in stiffness factor is governed by percentage of opening.

Percentage of Opening – (Area of Opening / Area of Infill Walls)

For Clay Brick Masonry – Em = 2970 N/mm2

Size of Infill Wall	Value of Stiffness Factor in X direction	Value of Stiffness Factor in y direction	Percentage of Opening	Width of Strut in X Dir.	Width of Strut in Y Dir.
110 mm	3.1	2.36	0%	520 mm	580 mm
110 mm	3.875	2.95	25%	475 mm	530 mm
110 mm	4.65	3.54	50%	440 mm	495 mm
200 mm	3.6	2.82	0%	490 mm	540 mm
200 mm	4.5	3.525	25%	450 mm	495 mm
200 mm	5.4	4.23	50%	415 mm	460 mm

For Fly Ash Brick Masonry - Em = 3220 N/mm2

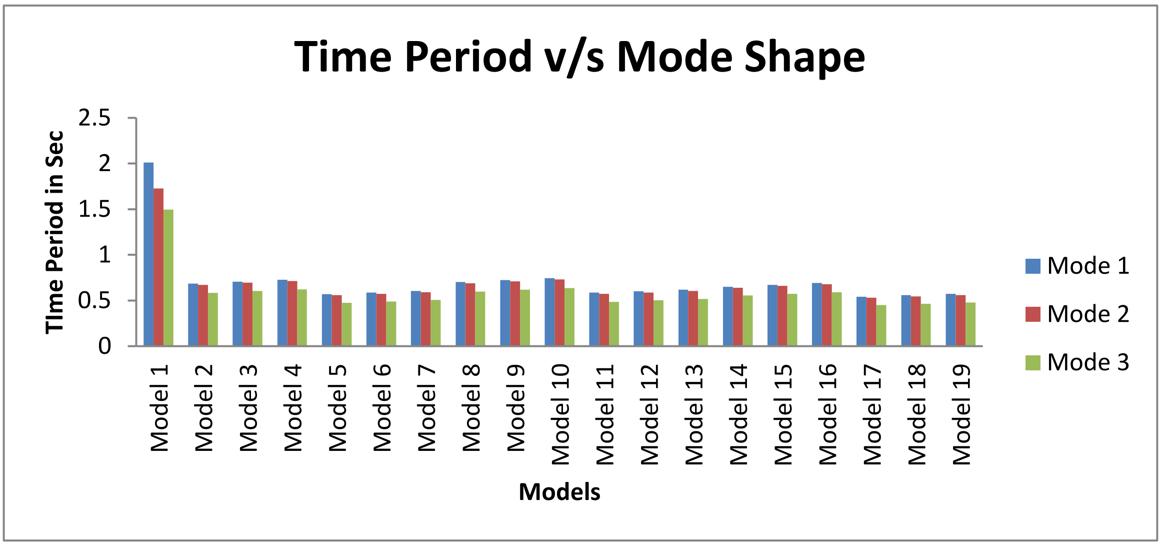
Size of Infill Wall	Value of Stiffness Reduction Factor	Value of Stiffness Reduction Factor	Percentage of Opening	Width of Strut in X Dir.	Width of Strut in Y Dir.
110 mm	3.1682	2.41192	0%	515 mm	570 mm
110 mm	3.96025	3.0149	25%	470 mm	520 mm
110 mm	4.7523	3.61788	50%	435 mm	490 mm
200 mm	3.6792	2.88204	0%	485 mm	530 mm
200 mm	4.599	3.60255	25%	445 mm	490 mm
200 mm	5.5188	4.32306	50%	410 mm	455 mm

For Concrete Block Masonry - Em = 2300 N/mm2

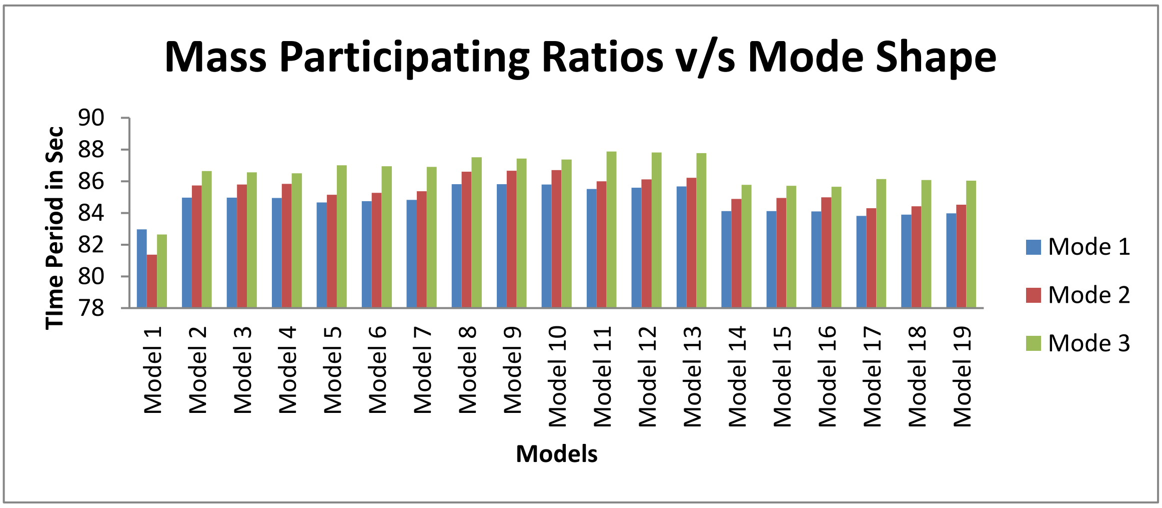
Size of Infill Wall	Value of Stiffness Reduction Factor	Value of Stiffness Reduction Factor	Percentage of Opening	Width of Strut in X Dir.	Width of Strut in Y Dir.
110 mm	2.9078	2.21368	0%	530 mm	600 mm
110 mm	3.63475	2.7671	25%	485 mm	545 mm
110 mm	4.3617	3.32052	50%	450 mm	505 mm
200 mm	3.3768	2.64516	0%	500 mm	555 mm
200 mm	4.221	3.30645	25%	460 mm	505 mm
200 mm	5.0652	3.96774	50%	425 mm	470 mm

4. RESULTS –

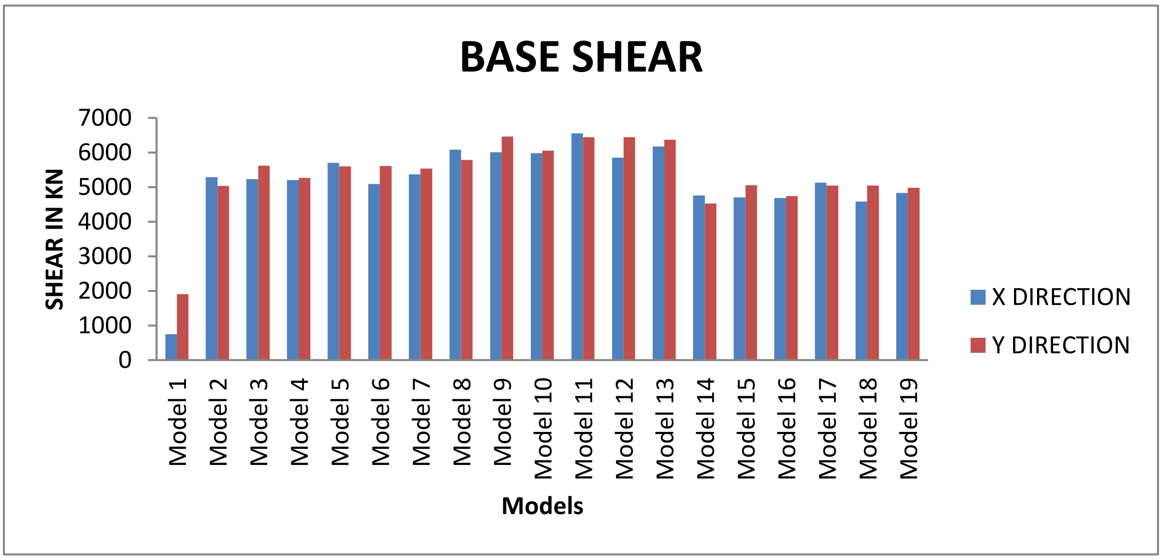
Time Period & Mode Shapes –



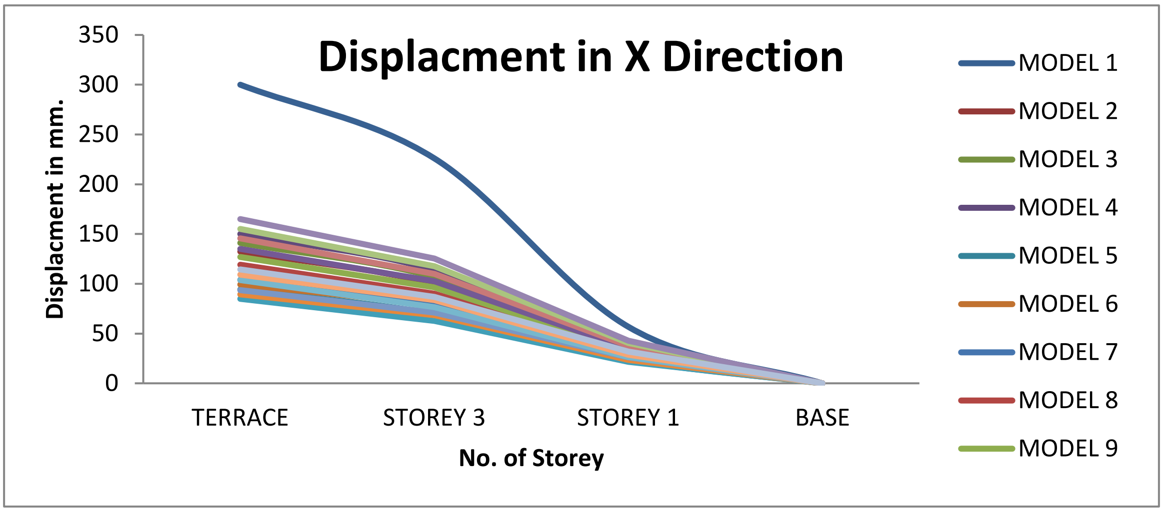
Mass Participation Ratios & Mode Shapes –



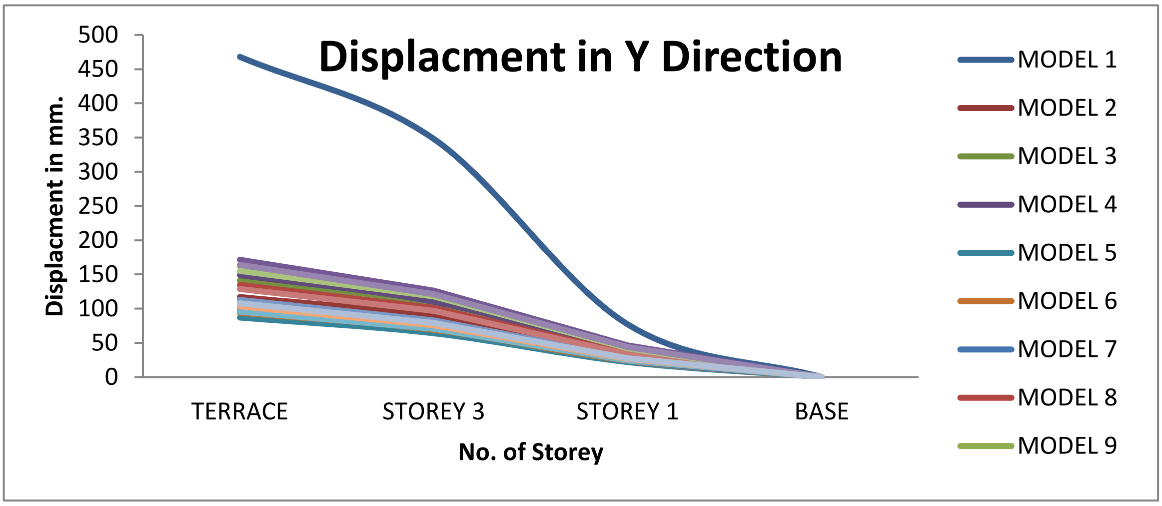
BASE SHEAR

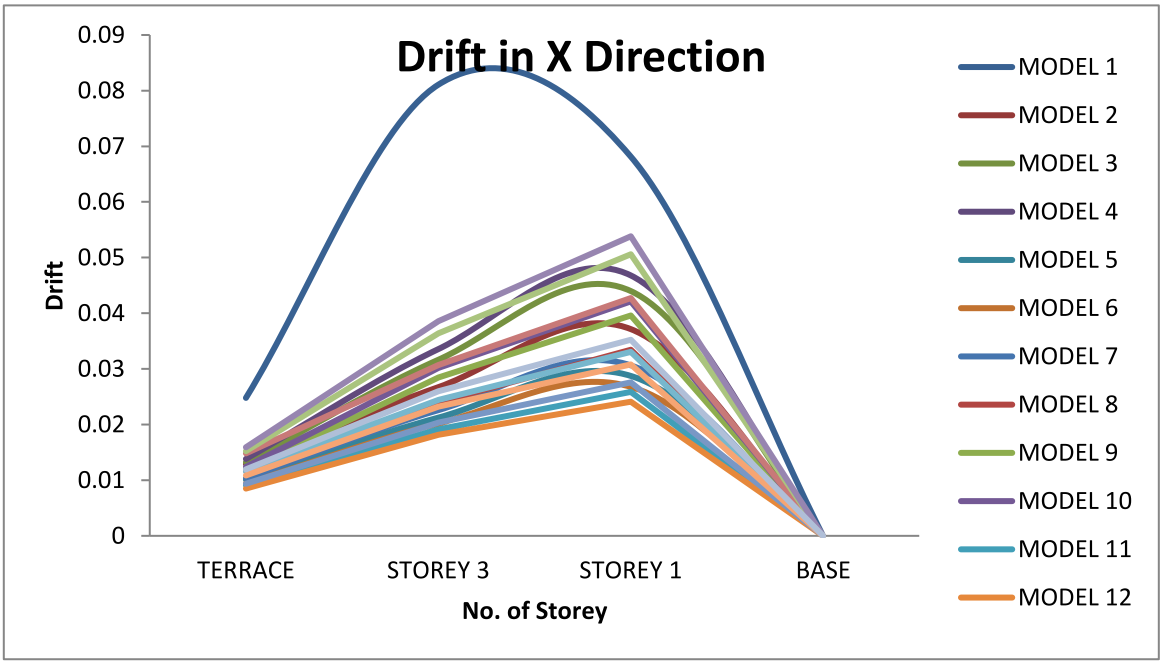


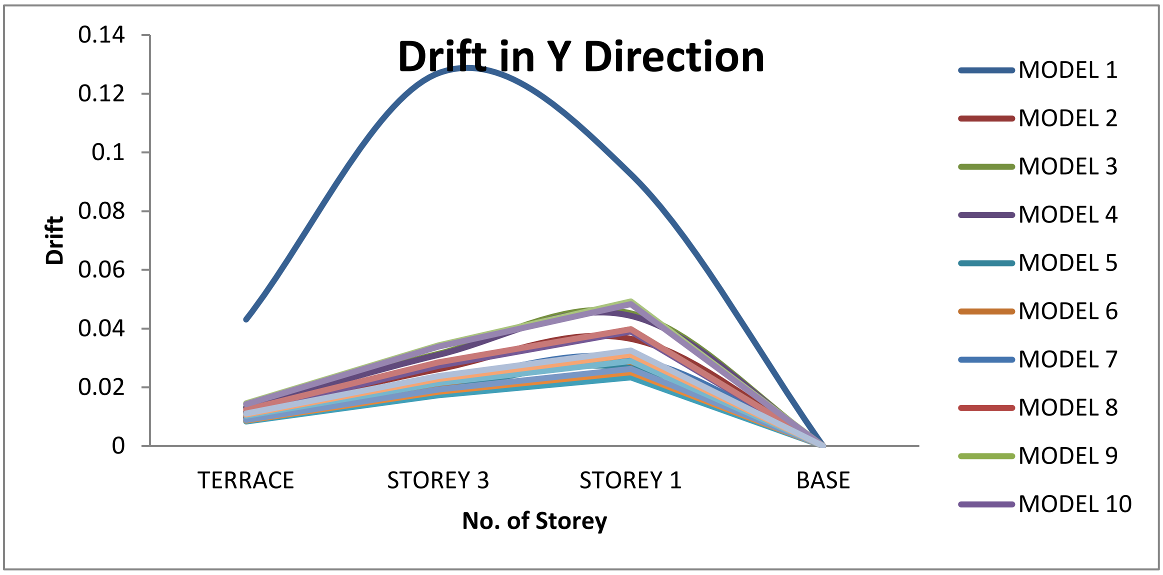
DISPLACEMENT



Drift







5. CONCLUSION

- The Time period of the RC structure with Infill is less than the RC structure without infill. The Natural Time Period also increases up to 3 % for fly ash type brick while the value decreases for concrete blocks up to 5 % when they compared to red burnt clay bricks.
- In RC structure without Infill, the storey displacement in X-direction and Y-direction is more when compared to RC structure with infill as shown. While comparing on the basis of material properties, fly ash bricks shows less values as compared to other two types of bricks. While the thickness of 200 mm shows less displacement values than 110 mm thick wall.
- In X-direction and Y-direction, the storey drift is less for RC without Infill structure than RC structure with infill. While comparing on the basis of material properties, fly ash bricks shows less values up to 10 % as compared burnt clay brick while the value of drift for concrete block is 15 % higher than the value with conventional bricks.
- With the thickness of 200 mm wall, the value of drift is found 20% less than with the 110 mm thick wall, which show the stiffness value of the structure increases with the increment of thickness of masonry wall.
- In the presence of infill wall, the stiffness of the structure and base shear increases. While for fly ash brick material the value of base shear is 10% higher than the conventional brick and for concrete blocks, it will reduce up to 15%. Hence, the lateral load resisting mechanism of infill frames differs from bare frames.

Recommendation –

All the parameter discussed in the study, have a considerable reduction for structure with infill wall which would result in over estimation of seismic influence on structure resulting in over considerate design, which could considerably be optimize with reference to the results discussed above. A consideration is necessary regarding the increment in storey shear in case of the presence of infill wall which is to be given new consideration in designing structure to resist seismicity. Influence of ductility ratio for structure with infill wall can be considered to analyse the seismic performance. The influence of percentage of opening in infill wall also needs to be considered for the actual behaviour of the structure. With fly ash brick material, the response of the structure against the lateral load seems to be quite preferable than conventional bricks and blocks.

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