Seismic Soil Structure Interaction of Buildings with Rigid and Flexible Foundation

Amar R Chougule[1], S S Dyavanal [2]

[1]Research Scholar and Asst. Professor, Department of Civil Engineering, KLECET, Chikodi,

[2]Professor, Department of Civil Engineering, B.V.B.C.E.T., Hubballi

Abstract: ***The effect of soil-structure interaction is generally ignored in the design process of low-rise buildings resting on shallow foundations though it has been shown that ignoring such effect may lead to unsafe seismic design. When a structure is subjected to an earthquake excitation, it interacts the foundation and soil, and thus changes the motion of the ground. It means that the movement of the whole ground structure system is influenced by type of soil as well as by the type of structure. An attempt has been made in this paper to study the effect of Soil-structure interaction on multi storeyed buildings with various foundation systems. Also to study the response of multi storeyed buildings subjected to seismic forces with Rigid and Flexible foundations subjected to seismic forces were analysed under different soil conditions like hard, medium and soft. A conventional G+6 storied building when rests on different soils is chosen for the study. The influence of soil-structure interaction is compared with the results obtained when the structure is assumed to be fixed at the base.***

Keywords: Soil structure interaction, Natural period, Base shear, Fixed base, Flexible base, Soil stiffness, Storey drift.

1. Introduction

In the last three decades, the effect of SSI on earthquake response of structures has attracted an intensive interest among researchers and engineers. Most of these researches focus on theoretical analysis, while less has been done on the experimental study. The interaction among the structure, foundation and soil medium below the foundation alter the actual behavior of the structure considerably as obtained by the consideration of the structure alone. Flexibility of soil medium below foundation decreases the overall stiffness of the building frames resulting in an increase in the natural period of the system. Soil-Structure Interaction (SSI) is a collection of phenomena in the response of structures caused by the flexibility of the foundation soils, as well as in the response of soils caused by the presence of structures. Analytic and numerical models for dynamic analysis typically ignore SSI effects of the coupled in nature structure-foundation-soil system. It has been recognized that SSI effects may have a significant impact especially in cases involving heavier structures and soft soil conditions. A parametric study is carried out for determining the lengthened lateral natural period of building frame due to incorporation of the effect of soil structure interaction. The study includes the building with isolated footing on soft, medium and hard soil and comparison between the natures of change in lateral natural period has been presented. Such a study may help to provide guidelines to assess more accurately the seismic vulnerability of building frames and may be useful for seismic design. The primary issues involved in the phenomenon of soil-structure interaction is the seismic waves propagate through soil during an earthquake, a discontinuity in the medium of wave's propagation is encountered at the interface of soil and structural foundations. The change in the material properties leads to scattering, diffraction, reflection and refraction of the seismic waves at the soil foundation interface their by changing the nature of ground motion at that point from what would have otherwise been observed in the absence of structure and foundation. The overall lateral stiffness of any building decreases due to the compressibility of soil. This leads to a subsequent increase in the natural periods of the structural system. Hence the effect of soil-structure interaction on the structural system resting on isolated foundation needs a detailed investigation. The soil-structure interaction may not be considered in the seismic analysis for structure supported on rock or rock like material.

2. Pushover Analysis

The recent advent of performance based design has brought the nonlinear static pushover analysis procedure to the forefront. Pushover analysis is a static, nonlinear procedure in which the magnitude of the structural loading is incrementally increased in accordance with a certain predefined pattern. With the increase in the magnitude of the loading, weak links and failure modes of the structure are found. The loading is monotonic with the effects of the cyclic behavior and load reversals being estimated by using a modified monotonic force-deformation criteria and with damping approximations. Static pushover analysis is an attempt by the structural engineering profession to evaluate the real strength of the structure and it promises to be a useful and effective tool for performance based design.

The ATC-40 and FEMA-273 documents have developed modeling procedures, acceptance criteria and analysis procedures for pushover analysis. These documents define force-deformation criteria for hinges used in pushover analysis. As shown in Figure 1, five points labeled A, B, C, D, and E are used to define the force deflection behavior of the hinge and three points labeled IO, LS and CP are used to define the acceptance criteria for the hinge. (IO, LS and CP stand for Immediate Occupancy, Life Safety and Collapse Prevention or Structural stability level respectively.) The values assigned to each of these points vary depending on the type of member, soil properties on which the structure is founded as well as many other parameters defined in the ATC-40 and FEMA-273 documents.

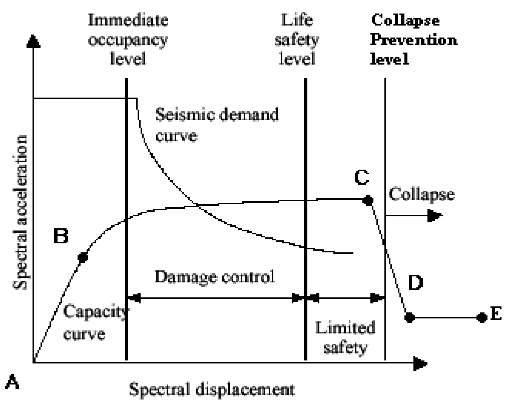

Figure 1: Force-Deformation for Pushover Hinge

3. Description of Building

For the purpose of the present seismic investigation, the plan and elevation are shown in Figure 2 and Figure 3. The idealized form of a typical 15m x 15m each bay of 3m width G+6storey building with brick infill and bare frame modeled in ETAB software. The bottom storey height is kept 4.8m and a typical height of 3.6m is kept for all the other storeys. To study the effect of soil flexibility, Wrinkler spring model a set of linear elastic springs are used. The stiffness of the springs is used to represent soil flexibility. Design data for the building considered are, Grade of concrete M25, Fe415, Ec=25.0 x 106kN/m2, Em=21.0 x 105kN/m2, Slab thickness = 0.12 m, Beam size = 0.30 x 0.60, Column size = 0.30 x 0.50 m, thickness of wall = 0.23 m, Roof finishes =2.0 kN/m2, Floor finishes = 1.0 kN/m2.Live Load intensities, Roof = 1.5 kN/m2, Floor = 3.0 kN/m2, Earthquake Live load on slab as per clause 7.3.1 and 7.3.2 of IS 1893(part 1)-2002 is considered i.e., for roof = 0% and for floor = 25% and seismic zone III. Building has no walls in the ground storey and masonry infill is modeled as equivalent diagonal strut in the upper storeys. Stafford Smith equation for calculation of equivalent diagonal strut width is considered. Stiffness of the masonry infill walls is considered. [1]

S. Smith and Hendry (1963)	$W = \frac{1}{2}\sqrt{\alpha^2{}_h + \alpha^2{}_L}$

Concrete frame elements are classified as beam and column frames. Columns and beams are modeled using three dimensional frame elements. Slabs are modeled as rigid diaphragms. The analytical model of the floor diaphragm represents the strength, stiffness and deformation capacity for in-plane loading. The beam-column joints are assumed to be rigid. Default hinge properties available in ETABS as per the ATC-40 are assigned to the frame elements. Default moment hinge M3 is assigned to beams; default axial and moment hinges PMM are assigned to columns and default axial hinges P are assigned to the equivalent diagonal struts. P-Δ effects are also considered in analysis and design of building models.

3.1 The different building models considered for the study are described as follows:

Model I: The bare frame building is founded on rigid (fixed) base.

Model II: The bare frame building is founded on stiff soil.

Model III: The bare frame building is founded on medium soil.

Model IV: The bare frame building is founded on soft soil.

Model V: The brick infill frame building is founded on rigid (fixed) base.

Model VI: The brick infill frame building is founded on stiff soil.

Model VII: The brick infill frame building is founded on medium soil.

Model VIII: The brick infill frame building is founded on soft soil.

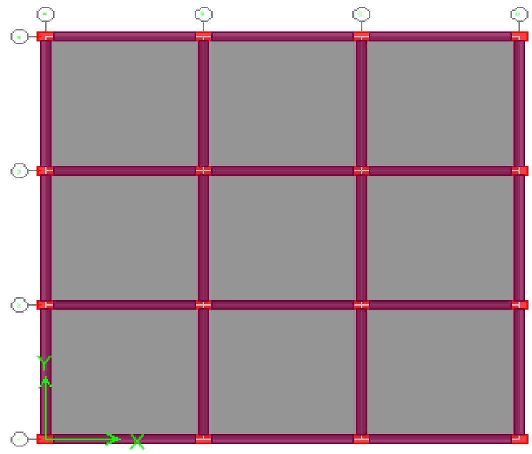

Figure 2: Plan

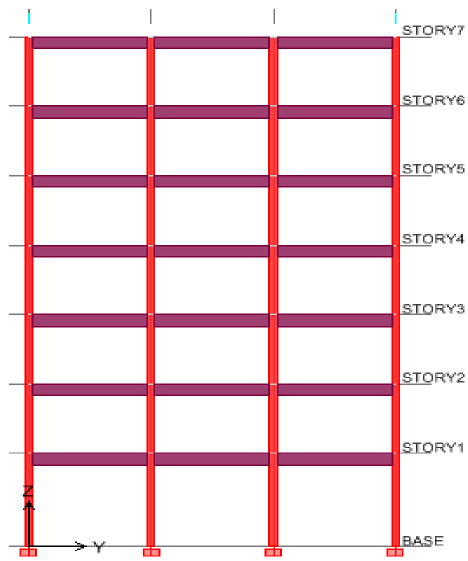

Figure 3a: Elevation (Bare Frame)

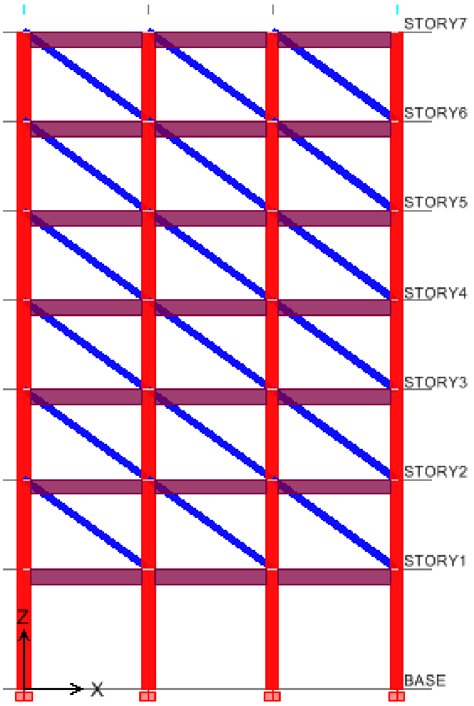

Figure 3b: Elevation (Brick Infill Frame)

3.2 Structural Modeling and Analysis Method

In the present analysis, the beams and columns are modeled as frame element and slab are modeled as rigid diaphragms. The slab is assigned membrane type behavior to provide in plane stiffness. All the masses of the floor are lumped at centre of rigidity, the beam column joints are assumed to be rigid. And all the models are analyzed and designed for Gravity load case i.e. 1.5(DL+LL). This behavior of soil has been simulated by modeling the same with a set of linear elastic springs. Below the centre of gravity of the foundation, three translational springs along mutually perpendicular global axes together with two rotational springs about these mutually perpendicular global axes are assigned to simulate the effect of soil-flexibility. ATC-40 has prescribed the procedure for modeling and calculating the stiffness of equivalent soil springs along the various degrees of freedom. The surface stiffness factors are multiplied with stiffness of embedment factors to consider the effects of the depth of bearing and then the individual distributed stiffness intensities are calculated by dividing the uncoupled total embedded stiffness by the corresponding area of contact for translational stiffness parameters and by moment of inertia for rotational stiffness parameters. To obtained the final stiffness with appropriate units (kN/m for translational and kN/radiance for rotational), individual distributed stiffness intensity parameters obtained above are multiplied with the corresponding areas. Soil parameters used to calculate these equivalent springs are tabulated in table 1.

Table 1: Soil parameter considered [4]

Type of Clay	*S.B.C of soil kN/m2*	*Young's Modulus kN/m2*	*Poisson ratio*	*Shear Modulus kN/m2*
Soft	120	15000	0.45	5172.41
Medium	160	50000	0.45	17241.37
Stiff	250	200000	0.45	68965.51

4. Results and Discussions

The results in terms of fundamental natural period, lateral displacements, storey drift and base shear for building models are presented and compared for different analysis. An effort is made to investigate the effect of soil structure interaction and nonlinear behavior of the building in the seismic analysis. Further, the building models with bare and brick infill frame models are evaluated using nonlinear static pushover analysis, in which the performance of the building models for the design earthquake are presented.

4.1 Fundamental Natural Period

The fundamental natural periods of bare frame and brick infill building models supported on different soil types for gravity design and seismic design are plotted in Fig 4a & Fig 4b. As in seismic design combination given in IS 1893 (Part 1): 2002, the sections of structural members are obviously larger as compared to those of gravity design combination. Hence, the stiffness of the building designed for seismic loads is much more which results in decrease in natural period. The stiffness of the gravity designed building is increased by retrofitting the corner walls at the ground storey hence there is decrease in natural period, compared with that of gravity designed.

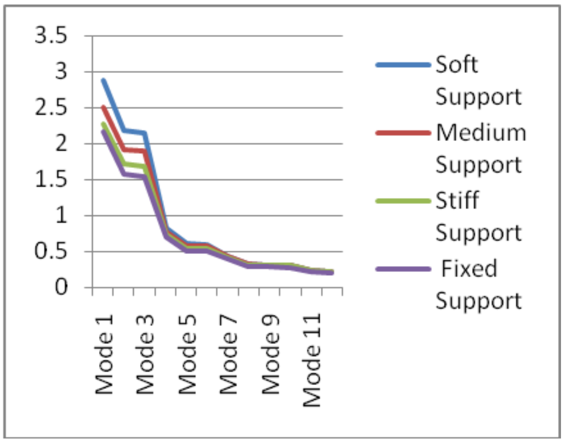

Figure 4a: Fundamental Natural Period on Bare Frame

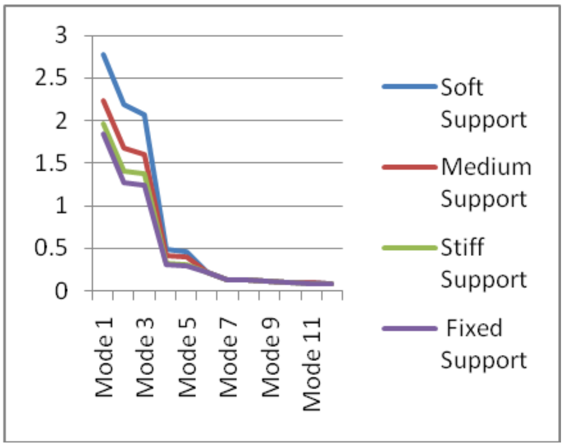

Figure 4b: Fundamental Natural Period on Brick infill Frame

4.2 Base Shear

The base shear is a function of mass, stiffness, height, and the natural period of the building structure. In the equivalent static method design horizontal acceleration value obtained by natural period given in code is adopted, and the basic assumption in the equivalent static method is that only first mode of vibration of building governs the dynamics and the effect of higher modes are not significant therefore, higher modes are not considered in this method. The base shear of bare frame and brick infill building models supported on different soil types for gravity design and seismic design are plotted in Fig 4c & Fig 4d.

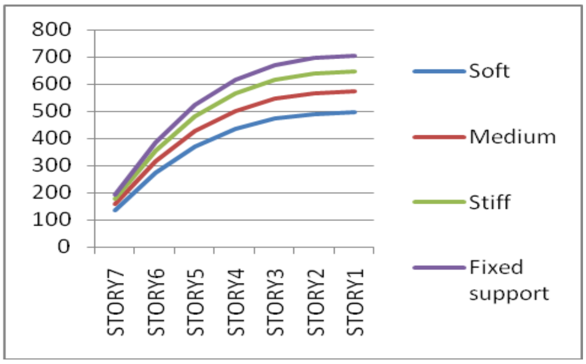

Figure 4c: Base shear for Bare Frame

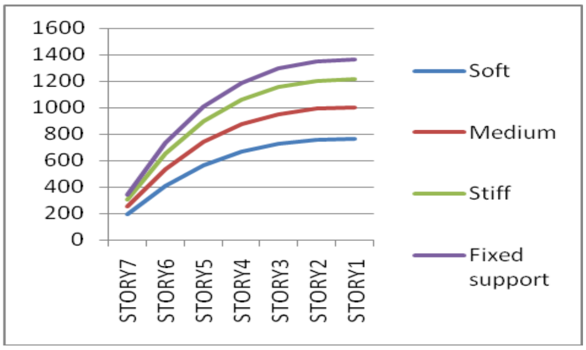

Figure 4d: Base shear for Brick infill Frame

4.3 Change in lateral displacements

Lateral displacements for different soil type are tabulated in figures 4e and 4f along longitudinal direction. From the figures it is observed that the displacement values are increasing as the soil type changes from rigid to soft.

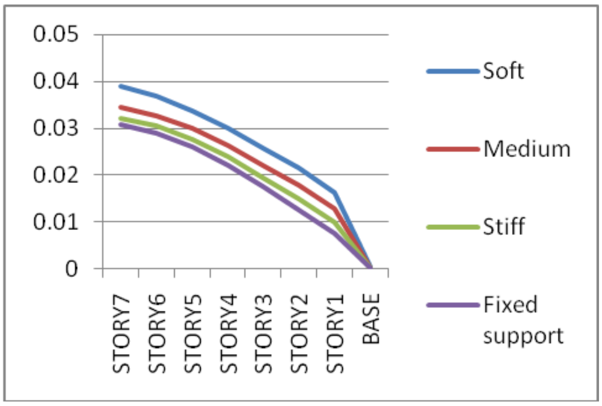

Figure 4e: Lateral displacement for Bare Frame

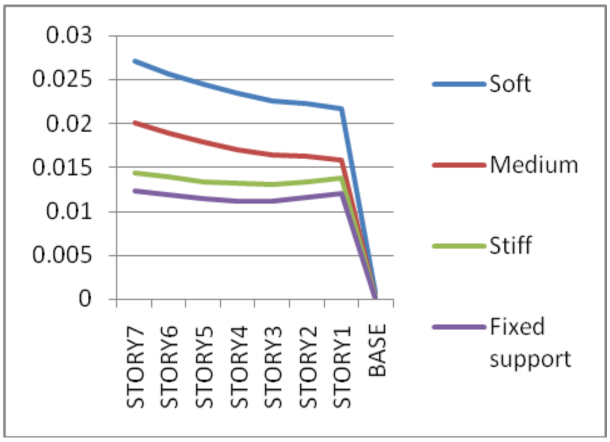

Figure 4f: Lateral displacement for Brick infill Frame

4.4 Inter Storey Drift

The variation of the inter storey drift for the building models along the longitudinal direction are shown in the Figs. 4g and 4h. Due to the open ground story of model 2 the inter storey drift was found to be more in the first storey along longitudinal direction. As per IS 1893 (Part 1): 2002, clause 7.11.1. The storey drift should not exceed 0.004 times the storey height. For the upper storeyes of model 2, the storey drifts are with in limit but for the first storey it is exceeding the permissible limits because it possess stiffness irregularity due to the open ground storey

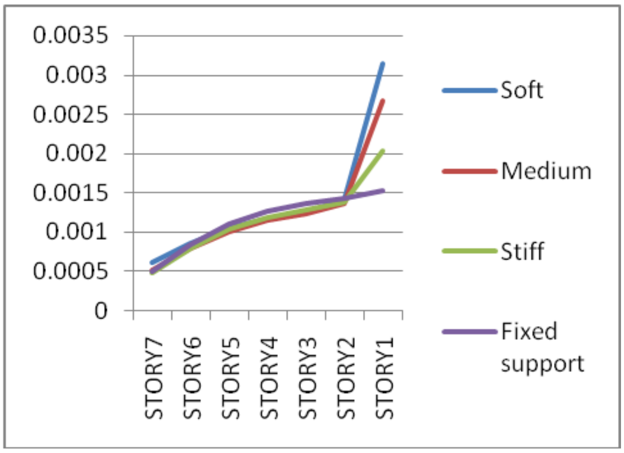

Figure 4g: Storey drift for Bare frame

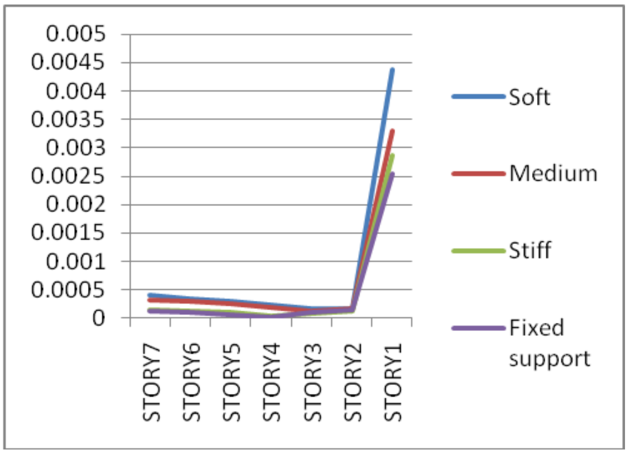

Figure 4f: Storey drifts for Brick Infill frame

4.5 Performance Evaluation of Building Models

Performance based seismic evaluation of all the models is carried out by nonlinear static pushover analysis. Default hinges are assigned for the most severe designed load combination for building models.The pushover analysis was including ten steps. It has been observed that, on subsequent push to building, hinges started forming in beams first. Initially hinges were in B-IO stage and subsequently proceeding to IO-LS and LS-CP stage. The performance points for building models are tabulated in table 2. Where V and D are the base shear and displacement respectively.

Table 2. Performance Point (V, D)

Soil Type	*Bare Frame*		*Brick Infill Frame*	
	V	*D*	*V*	*D*
Fixed base	1244.28	0.249	1634.40	0.076
Stiff soil	1241.29	0.255	1628.78	0.079
Medium Soil	1234.70	0.270	1603.69	0.090
Soft Soil	1178.11	0.290	1348.29	0.112

In most of the buildings, all the plastic hinges are formed in the first storey because of open ground storey. The plastic hinges are formed both in the beams and columns. Performance of the buildings lies in the collapse prevention range for bare frame and brick infill frame supported on all the types of soil. As the building is supported on soft soil, most of the plastic hinges are formed in the columns and beams of the first story and it is observed that plastic hinges are not at all formed in upper storeyes. Considering at the performance point, the plastic hinges are formed along both the longitudinal and transverse directions; the performance is found to be within the range of life safety and collapse prevention where the major structural components may get damaged but does not get collapsed and there is no threat to life safety either within or outside the building. While injuries during the earthquake may occur, the risk of life threatening from the structural damage is very low. However these buildings can be retrofitted and the performance of the building can be increased to life safety range.

At performance point, where the capacity and demand meets, out of 560 assigned hinges in bare frame on soft soil 412 were in A-B stage, 60, 24, 48, 0, 1 and 15 hinges are in B-IO, IO-LS, LS-CP CP-C, C-D and D-E stages respectively. As at performance point, hinges were in LS-CP range. Overall performance of bare frame buildings is said to be life safety to collapse prevention stage. Also out of 848 assigned hinges in brick infill frame on soft soil 823 were in A-B stage, 5, 4, 14, 0, 0 and 2 hinges are in B-IO, IO-LS, LS-CP CP-C, C-D and D-E stages respectively. As at performance point, hinges were in LS-CP range. Overall performance of brick infill frame buildings is said to be life safety to collapse prevention stage.

5. Conclusions

From the results discussed with respect to the building models considered leads to the following conclusions:

1. It is observed that the fundamental natural frequencies increase and base shears decrease with the increase of soil stiffness and this change is found more in soft soils.
2. The seismic response of the building frames such as Lateral deflection, Storey drift, and Base shear values were compared for both type of building frames. Lateral deflection, Storey drift, and Base shear values increases when the type of soil changes from hard to medium and medium to soft for fixed and flexible base buildings.
3. Lateral deflection, Storey drift, and Base shear values of fixed base building was found to be lower as compared to flexible base building. Hence suitable foundation system considering the effect of Soil stiffness has to be adopted while designing building frames for seismic forces.
4. Performance points of all building models were observed before the collapse prevention of the building and is concluded that the injuries during the earthquake may occur, the risk of life threatening from the structural damage is very low. However these buildings can be retrofitted and the performance of the building can be increased to life safety range.
5. Soil–structure interaction cannot be ignored while designing important structures like buildings, bridges, nuclear power plants, liquid storage structures, dams etc., against expected earthquake forces.
6. Software used for nonlinear static analysis ETABS 9.7 having features of performing performance based analysis by going through some simple steps.

References

[1] Agarwal. P. and Shirkhande. M., 2006 “Earthquake resistant Design of Structures” Printice- Hall of India Private Ltd. New Delhi, India
[2] Applied Technology Council, (1996), “Seismic Evaluation and Retrofit of Concrete Buildings”, ATC 40, Vol. 1, Applied Technology Council, Redwood City, California
[3] Das, D. and Murty, C.V.R. (2004). “Brick masonry infills in seismic design of RC framed buildings Part 2”: The Indian Concrete Journal pp 31-37.
[4] Devid J. Dowrick, “Earthquake resistant design for engineering and architects” second edition, Jhon Wiley & Sons, New York
[5] Hemant B Kaushik, Durgesh C. Rai, and Sudhir K. Jain, “Code Approaches to Seismic Design of Masonry-Infilled Reinforced Concrete Frames: A State-of-the-Art Review”
[6] IS:1893 (Part 1)–2002 Criteria for Earthquake Resistant Design of Structures, Part 1-General provisions and buildings, fifth revision, Bureau of Indian Standards, New Delhi, India.
[7] IS:456-2000, “Code of Practice for Plain and Reinforced Concrete”, Bureau of Indian Standards, New Delhi, India