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Study on Dynamic Characteristics of 3D Reinforced Concrete Frame with Masonry Infill

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Comprehensive experimental and numerical studies are carried out on the dynamic characteristics of 3 dimensional (D) reinforced Concrete (RC) frame with Masonry Infill (MI). MI though considered as non-structural element largely affect strength, stiffness and ductility of the framed structure during the application of lateral loads such as wind and earthquake loads. This paper is a part of a collaborative research project between CPRI and BARC focusing on the influence of MI on the natural frequencies of 3D RC frame and comparison of the results with the design codes. A 3D RC frame having two bays and three storeys is designed and detailed as per the relevant Indian standard codes. A simple numerical model is being formulated to obtain the natural frequencies in the FE analysis and Tri-axial shake table of 3m x 3m is used for the experimentation. The details of the numerical analysis and experiments carried out in the research work are brought out in this paper.

Keywords: *RC frame, Masonry Infill, natural frequency, shake-table test*

1.0 INTRODUCTION

Reinforced concrete frames are a common structural system for buildings worldwide. Masonry infills are a part of RC frames as it provides excellent insulation and isolation from climatic forces such as heat, sun, wind, rains, extreme cold, etc. The infills are invariably constructed after the basic framework of beams, columns and slabs have gained sufficient strength. As a result, the bond of infill with the reinforced concrete framework is negligible at the sides and top surface of the wall. Therefore, they are classified as non-structural elements and the structures are analysed and designed by considering them only as dead mass. This assumption of neglecting the effects of infill is a reasonable and justifiable for the structure under gravity loads. However, the same is not true for the structures with infill when subjected to lateral loads, especially seismic loads. Extensive research is being carried out worldwide in the last five decades to study the influence of MI on natural frequency of RC frames. Many methods have been developed for the dynamic analysis of RC frames with MI incorporating one or more simplifying assumptions regarding its stiffness. With this background, a collaborative research work is taken up to investigate the dynamic performance of 3D RC frames with and without infills. The RC frame is designed as per Indian Standard codes IS: 456-2000, IS: 1893-2002 (zone V) and detailed as per IS: 13920-1993. A tri-axial shake table with six degrees of freedom is used to conduct the experiments.

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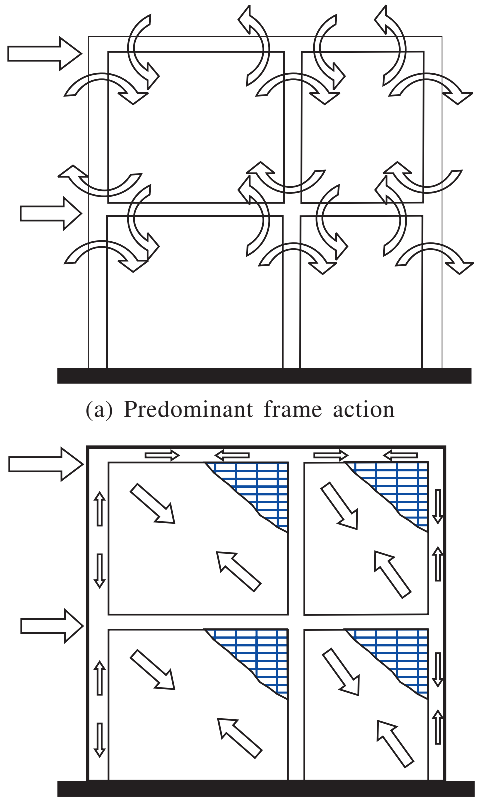
2.0 BACKGROUND

Infill walls have a very high initial in-plane lateral stiffness and low deformability. Therefore, under seismic loads, the existence of infill walls change the whole lateral force transfer mechanism of the structure from a predominant frame action to predominant truss action as shown in Fig. 1 (Murty and Jain, 2000). The change of frame mechanism to truss mechanism leads to a two-fold action. One, which in general is beneficial, it leads to reduction in bending moments and increase in axial forces in the frame members; and two, which is more severe, it changes the natural frequency of the system significantly due to large stiffness addition which is generally not traded off completely by increase in mass due to walls. Paulay and Priestley (1992) caution that although masonry infill may increase the overall lateral load capacity, it can result in altering structural response and attracting forces to different or undesired parts of structures with asymmetric arrangements.



(a) Predominant frame action

(b) Predominant truss action

FIG. 1 LATERAL LOAD TRANSFER MECHANISM DUE TO MI PANELS (MURTY AND JAIN 2000)

The analytical modeling of infill frames is a complex issue, because these structures exhibit highly non-linear inelastic behaviour, resulting from the interaction of the masonry infill panel and the surrounding frame (Singh and Das, 2006). Generally, the available modeling approaches for masonry infill can be grouped into micromodels and macromodels. Micro-models capture the behaviour of infill and its interaction with the frames in much detail, but these models are computationally expensive. On the other hand, macromodels try to capture the gross behaviour of the infill, are approximate but computationally efficient (Singh and Das, 2006).

Under macromodels, Smith (1962) studied the lateral stiffness of infill frames by assuming an equivalent diagonal strut to replace the infill and the effective width of the equivalent strut varied from d/4 for a square infill to d/11 for an infill having a side ratio of 5:1, where d is the diagonal length of infill. Smith and Carter (1969) examined the behaviour of multi-storey infill frame under lateral loading. The main objective of their study was to obtain reasonable information about stiffness and strength of horizontally loaded infill frames. Thiruvengadam (1985) proposed multiple strut model of infill panel by considering reciprocal stiffening effect. The model consists of a moment resisting frame with a number of pin-jointed diagonal struts in both the directions. Lotfi (1994), Saneinejad and Hobbs (1995), Madan et al (1997) have also proposed some of the more popular strut models for modeling of infill panels. Das and Murty (2004) performed analysis and design on five RC frame buildings with brick masonry infill designed as per Eurocode, Nepal code, Indian code and the equivalent braced frame methods and concluded that infill reduces the structural drift and overall structure ductility, but increase the overall strength and stiffness. Korkmaz *et al.* (2007) adopted the diagonal strut approach for modeling masonry infill walls and pushover curves were obtained for the structures using non-linear analyses. Kaushik *et al.* (2006) gave a good comparison of the formulations recommended by various national and international standards and concluded that no single code contains all the relevant information required for the seismic design of structures.

3.0 CONSTRUCTION OF 3D RC FRAME

The dimensions of 3D RC frame is considered in such a way to fully utilize the dimensions of 3m x 3m and payload capacity of 100 kN of the tri-axial shake table at Earthquake Engineering and Vibration Research Centre (EVRC), Central Power Research Institute (CPRI), Bangalore. The 3D frame has two bays and three storeys with the details as shown in Table 1.

TABLE 1

DETAILS OF 3D RC FRAME

Details	**3D RC frame**
No. of storeys	3
No. of bays	2 along each axis
Storey height	0.9 m
Bay width	1.2 m
Beam and column	75 mm x 100 mm
Longitudinal reinforcement	4-6 ø in beam, 4-8 Tor in column
Transverse reinforcement	2L-3 ø @75mm c/c
Slab	50 mm thick, 6 ø @100 mm c/c both ways in two layers
Concrete	M25
E_c	2.5 x 10^7 kN/m^2
E_m	1.4 x 10^7 kN/m^2

4.0 NUMERICAL MODELING

The numerical model used in this work is based on the well-known method proposed by Smith and Carter (1969). The width and modulus of elasticity of the equivalent strut to replace the masonry wall is estimated based on the formulation proposed by them. Various parameters affect the equivalent strut width namely geometric properties of infill, panel proportion, panel height, surrounding frame stiffness, material properties of frame and infill. The contact length, '$\acute{a}_h$', shown in Fig. 2 can be related with the relative stiffness of the infill to frame by the approximate equation given below

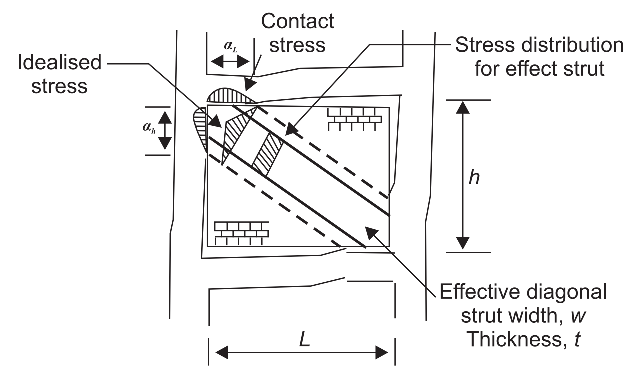


FIG. 2 EQUIVALENT DIAGONAL STRUT (DRYDALE, ET AL. 1994)

$$\alpha_h = \frac{\pi}{2\lambda_h} \tag{1}$$

where, 'λ_h' is an empirical parameter expressing the relative stiffness of the column to the infill and is given by,

$$\lambda_h = \sqrt[4]{\frac{E_m t \sin 2\theta}{4 E_c I_c h}} \tag{2}$$

Assuming $\alpha_L = \alpha_h$, where α_L is a parameter for contact length of beam member with the infill, the width 'w' of the equivalent diagonal strut is given by

$$w = \sqrt{\alpha_L^2 + \alpha_h^2} \tag{3}$$

$$w = 1.414\alpha_h \tag{4}$$

where;

E_m = Modulus of elasticity of masonry infill

t = Thickness of masonry infill

h = Height of masonry infill

E_c = Modulus of elasticity of column

I_c = Moment of inertia of the column

θ = Slope of the infill diagonal to horizontal

From the second equation, it can be seen that, instead of stiffness of both beam and column, this empirical parameter is related with only the column stiffness. It is propounded that whatever the beam stiffness is, beam contact length is always approximately half of its span. However, since the aim of this work is to develop a simplified model to obtain the natural frequency of the system with reasonable accuracy, certain simplifications are incorporated in the proposed model as given below.

1. The initial modulus of elasticity of the masonry is not modified any further.
2. The width of the strut is kept as $\mathbf{1.414\alpha_h}$.
3. The thickness of the strut is kept as the thickness of the wall.

It is found that these simplified calculations lead to reasonably good estimate of the natural frequencies.

5.0 FE ANALYSIS AND EXPERIMENTAL WORK ON 3D RC FRAME

5.1 FE analysis on 3D RC frame

The 3D RC frame is analysed using STAAD Pro. The equivalent diagonal strut elements are used for modeling of infills. The geometry of 3D model is developed as per the dimensions. Appropriate material, boundary conditions and properties are assigned and modal analysis is carried out to find the natural frequency of the structure. Fig. 3 shows FE model of 3D RC Frame. Mode shapes obtained in the in-plane and out-of-plane directions are shown in Figures 4, 5 and 6. The natural frequencies obtained from FE analysis are tabulated in Table 2.

FIG. 3 FE MODEL OF FIRST 3D RC FRAME

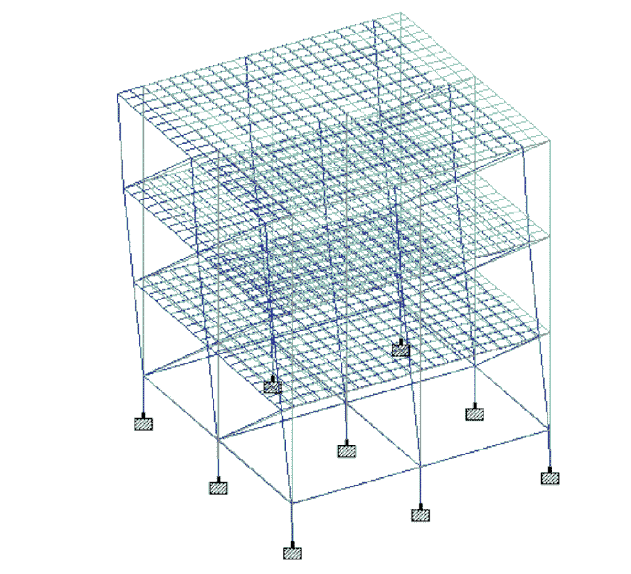


FIG. 4 I MODE IN OUT-OF-PLANE: 4.69 Hz

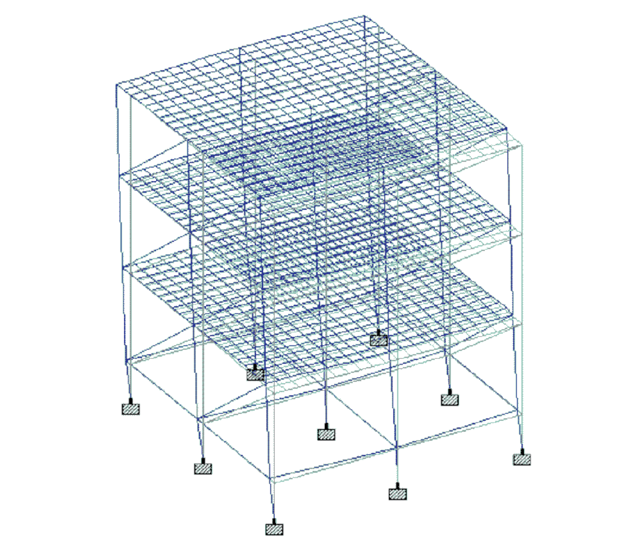


FIG. 5 II MODE IN IN-PLANE: 10.47 Hz

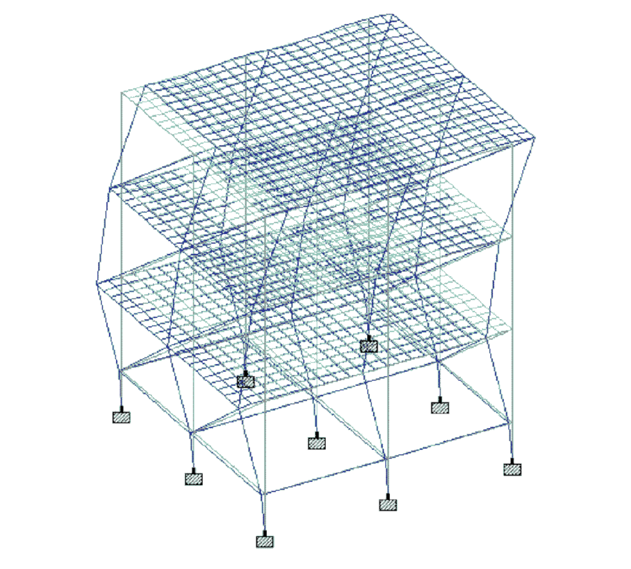


FIG. 6 III MODE IN OUT-OF-PLANE: 15.15 Hz

TABLE 2

FE ANALYSIS RESULTS OF 3D RC FRAME

Model	Plate Model Frequency (Hz)	Frequency (Hz)
3D RC	In-Plane	10.47
frame	Out of Plane	4.69, 15.15

5.2 Shake table tests on 3D RC frame

The 3D RC frame is constructed outside the laboratory and suitable arrangements are made to move the frame on the shake table. Precautions are taken such that no structural damage occurs during transportation and placing of the structure on the shake table. Forklift of 50 kN capacity is employed to carry the frames into the laboratory and then the 150 kN overhead crane is used to place the specimen on the shake table.

EVRC, housing the tri-axial shake table with six degrees of freedom is capable of performing a wide range of seismic qualification test requirements on structures, equipments, sub-structures and components as per National/ International standards. The tri-axial shake table can strictly simulate the earthquake ground motion without any distortion. The shake table of 3 m x 3 m can vibrate in one axis to three axes with six degrees of freedom with a payload of 100 kN capacity. The RC frame is mounted on the shake table as shown in Fig. 7. At specified locations on the frames, accelerometers are mounted. The accelerometers are interfaced to the data acquisition system.

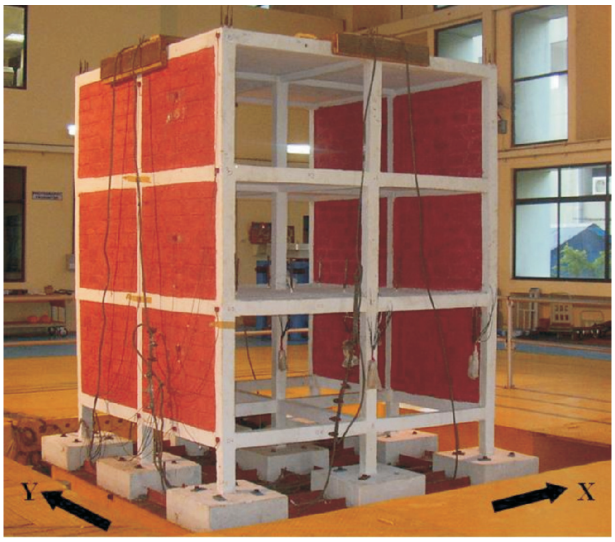


FIG. 7 FIRST 3D MODEL ON SHAKE TABLE

5.3 Resonance search test

In this test, a sinusoidal input with continuously varying frequency at 1octave/min is applied to the structure along the in-plane direction. The frequencies are varied from 1 to 50 Hz. This test produces the most thorough search for all resonant frequencies and it is customarily used for this purpose as an exploratory test, with a low input level (0.1g). At resonance frequency the transfer function (TF) of response to input motion generally exceeds 2, there is a phase shift between input and response motion and also there is a sudden dip in the coherence at that frequency.

5.4 Sine sweep tests on structure in-plane of walls (Y-direction)

Tests are conducted on the structure along the plane of walls. These tests are carried out to study the behaviour of brick walls under in-plane loads and to verify the effect of walls on characteristics of the structure. The tests are carried out for a frequency range of 1 to 50 Hz, with acceleration levels of 0.075g, 0.1g and 0.125g. During these tests, diagonal tension cracks at the corner of walls are observed first on ground storey walls at an acceleration of 0.1g and then on middle storey walls at an acceleration of 0.125g. This is as expected since the maximum diagonal tension will come at the bottom storey. Consequently, there is a gradual reduction in the fundamental frequency and increase in the amplification due to the de-bonding of the masonry infill with the RC frame. The results of sine sweep tests are summarized in Table 3.

TABLE 3 SUMMARY OF RESULTS OBTAINED DURING SINE SWEEP TESTS IN-PLANE DIRECTION WITH WALLS			
Acceleration level	**Visual observation**	**Resonant frequency**	**Amplification m/s²**
0.075 g	No cracking, No damage	9.75 Hz	5.16
0.1 g	Diagonal tension cracks in ground storey walls	9.25 Hz	6.17
0.125 g	Diagonal tension cracks in middle storey walls	8.75 Hz	8.50

5.5 Sine sweep tests on structure in vertical direction

A single test with an acceleration level of 0.1g is performed in Z-direction, but no resonance frequency is observed in the range of 1 to 50 Hz.

5.6 Sine sweep tests on structure out-of-plane of walls (X-direction)

Next set of tests are conducted along out-of-plane direction of walls. The tests are carried out for a frequency range of 1 to 50 Hz, with acceleration levels of 0.075g, 0.1g and 0.125g. During these tests, diagonal tension cracks formed earlier due to in-plane tests propagated throughout the periphery of the walls, first on middle storey walls at an acceleration of 0.1g and then on bottom storey walls at an acceleration of 0.125g. This is again as expected since the out-of-plane stresses will be experienced maximum by top storey. However, it should be noted that there is still no significant cracking in the top storey walls. This clearly highlights the fact that the out-of-plane strength of the walls is significantly reduced due to a simultaneous action of in-plane vibrations (as in the case of real earthquake scenarios). The results of sine sweep tests out-of-plane of the walls are summarized in Table 4.

TABLE 4 SUMMARY OF RESULTS OBTAINED DURING SINE SWEEP TESTS IN OUT-OF-PLANE DIRECTION				
Acceleration Level	Visual Observation	Resonant Frequency		Amplification m/s²
		1st Mode	2nd Mode	
0.075g	No cracking, No damage	4.50 Hz	17.00 Hz	10.00
0.1g	Peripheral cracks in middle storey	4.25 Hz	16.25 Hz	12.58
0.125g	Peripheral cracks in bottom storey	4.00 Hz	15.35 Hz	13.92

6.0 CODAL FORMULATIONS

Various national and international codes give empirical formulae to find the natural period of the structure. The natural frequencies calculated using Euro code 8-2003 and Indian code IS 1893-2002 are compared with the FE analyses and shake table test results are tabulated in Table 5. Indian code is similar to Egyptian code, Venezuelan code, Algerian code, Nepal code, Ethiopian code etc, and Euro code is similar to Costa Rican code, Philippines code etc (Kaushik *et al,* 2006).

The approximate fundamental natural period (T_a), in seconds, for moment-resisting frame building without masonry infill is estimated by the empirical expression which is similar in both the codes,

$$T_a = 0.075H^{0.75} \tag{5}$$

where,

H = Height of building, m

The approximate fundamental natural period (T_a), in seconds, of all other buildings, including moment-resisting buildings with masonry infills, is estimated by the empirical expression in Indian code IS 1893-2002,

$$T_a = \frac{0.09H}{\sqrt{D}} \quad (6)$$

where,

D = Base dimension of the building at the plinth level, in m, along the considered direction of the lateral force

Alternatively, for structures with masonry infill, Euro code 8-2003 recommends the following equations for calculating the fundamental natural period for buildings of up to 40 m height

$$T_a = C_t H^{0.75} \quad (7)$$

$$C_t = \frac{0.075}{\sqrt{A_c}} \quad (8)$$

$$A_c = \sum A_i \left(0.2 + \frac{l_{wi}}{H}\right)^2 ; \frac{l_{wi}}{H} \le 0.9 \quad (9)$$

where,

C_t = Correction factor for masonry infill

A_c = Total effective area of masonry infill in the first storey, m^2

A_i = Effective cross-sectional area of masonry infill 'i' in the first storey, m^2

l_{wi} = Length of the wall in the first storey in the direction parallel to the applied forces, m

H = Height of the Building, m

TABLE 5

NATURAL FREQUENCIES OBTAINED FROM IS CODE, EURO CODE, FE ANALYSES AND SHAKE TABLE TESTS

	3D RC frame	
	In-plane	Out-of-plane
Indian Code	5.65	5.58
Euro Code	5.65	4.11
FE analyses	4.69	10.47
Shake Table	4.50	9.75

7.0 CONCLUSIONS

The masonry infill panels, although do not interfere in the vertical load resisting system for the RC frame structures, they significantly affect the lateral load-resisting system of the same.

The natural frequency of the structure in the in-plane direction with complete infill is significantly higher than the natural frequency of the out-of-plane direction without infill. In most of the cases, the natural frequency of the frame in the in-plane direction with complete infill is found to be around twice as that of the out-of-plane direction without infill.

The effect of de-bonding of masonry infill with RC frame as the base acceleration increased is clearly seen in the shake table test results. Due to the de-bonding effect, the natural frequencies reduces whereas the magnification factor of the output acceleration increases.

The natural frequencies of 3D RC frame are high in presence of masonry infill. Hence the role of masonry infill in resisting the lateral forces like earthquake and wind is significant and has to be accounted during designing of the structures.

Indian code and Euro code which are similar to many international codes predicts with reasonable accuracy the natural frequencies of the RC frame without infill. But these standards give less value of natural frequencies when the masonry infill exists. Indian code does not consider the position or amount of infill present in the structure, whereas Euro code gives importance to the masonry in the first storey but the results of the Indian code are better compared to Euro code. Hence these shortcomings need to be validated through detailed experimental investigations.

The prediction of natural frequencies for 3D RC frames with masonry infill using the proposed formulation for the width of equivalent diagonal strut in FE analyses matches reasonably well with the shake table test results and is better compared to the results obtained using codal provisions.

8.0 ACKNOWLEDGEMENTS

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REFERENCES

[1] Das D and Murty C V R. "Brick masonry infills in seismic design of RC frame buildings: Part 2-Behaviour", The Indian Concrete Journal, 31-38, 2004.

[2] Drydale R G, Hamid A A and Baker L R. "Masonry structures-behaviour and design", *Prentice Hall*, Englewood cliffs, New Jersey, USA, 1994.

[3] Kaushik, H.B., Rai, D.C., and Jain. S.K., "Code approaches to seismic design of masonry-infilled reinforced concrete frames", Earthquake Spectra, Vol 22, No. 4, November 2006, pp. 961–983.

[4] Korkmaz K A, Demir F and Sivri M. "Earthquake assessment of R/C structures with masonry infill walls", International Journal of Science and Technology, Vol 2, No. 2, 2007, pp. 155–164.

[5] Lotfi H R and Shing P B. "An interface model applied to fracture of masonry structures", Journal of Structural Engineering, ASCE, 120(1): 1994, pp. 63–80.

[6] Murty C V R and Jain S K. "Beneficial influence of masonry infills on seismic performance of RC frame buildings", Proceedings, 12th World Conference on Earthquake Engineering, New Zealand, Paper No. 1790, 2000.

[7] Singh Y and Das D. "Effect of URM infills on seismic performance of RC frame buildings", 4th International Conference on Earthquake Engineering Taipei, Taiwan, October 12-13, 2006, paper No. 064, 2006.

[8] Smith B S. "Lateral stiffness of infilled frames", Journal of Structural Division, Proceedings of ASCE, December 1962, pp. 183–199, 1962.

[9] Smith B S and Carter C. "A method of analysis for infilled frames", Proc. ICE, Vol. 44, September 1969, pp. 31–48, 1969.

[10] Thiruvengadam V. "On the natural frequencies of infilled frames", Earthquake Engineering and Structural Dynamics, 13, pp. 401–419, 1985.

[11] Paulay T and Priestley M J N.(1992) "Seismic design of concrete and masonry buildings", John Wiley and Sons Inc., New York., 1992.

[12] European Committee of Standardization, Eurocode 8: "Design of structures for earthquake resistance—Part 1: General rules, seismic actions and rules for buildings", prEN1998-1, Brussels, Belgium, 2003.

[13] IS 456-2000 "Plain and reinforced concrete-code of practice," BIS, New Delhi, India.

[14] IS 1893-2002, "Criteria for earthquake resistant design of structures", Part 1: General provisions and buildings, fifth revision, BIS, New Delhi, India

[15] IS 13920-1993, "Ductile detailing of reinforced concrete structures subjected to seismic forces" -Code of Practice, BIS, New Delhi, India.

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