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THA of Three Storey RC Buildings under Varying Frequency Contents

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Abstract
The present work sheds light on the effects of varying frequency content (FC) of earthquake ground motions (GMs) on the behavior of three-story reinforced concrete (RC) regular frame buildings, modeled as a bare frame and soft open ground story (SOGS). It is extremely significant to know the characteristics of ground motion to avoid the vulnerability of structures. The important dynamic characteristics are peak ground acceleration (PGA), FC, and duration. Nine earthquakes with varying FC occurred earlier in different parts of the World and are performed on the building models to investigate the seismic fragility responses thoroughly. The base share calculated by equivalent static analysis (ESA) and response spectrum analysis (RSA) as per IS 1893 (Part 1): 2016 procedures, and linear time history analysis (LTHA) using ETABS 2015 are distributed along with the height of the building models. The building models' responses, namely: natural periods, base shear, roof displacement, inter-story drift, inter-story velocity, and inter-storey accelerations, and inter-storey stiffness, is also known as engineering demand parameters (EDPs), are presented. Authors conclude that the civil engineers can employ brick or concrete block infill walls in three-story RC buildings depending upon their availability and procurement cost at the construction site. There are no considerable changes in seismic responses. Additionally, the buildings built in earthquake-prone areas are analyzed with LTHA considering at least one earthquake GM with low or intermediate FC. Furthermore, all the maximum responses increase as the FC of the considered earthquakes decreases.

Keywords — *frequency content, peak ground acceleration, soft open ground story, linear time history analysis, engineering demand parameters.*

I. INTRODUCTION

Earthquakes cause random GMs in all directions, radiating from the epicenter. These GMs affect structure to vibrate, and thereby, inertia forces develop [1]. As a result, they cause social and economic consequences, deaths, injuries of lives, and damage to the surrounding environment. To take safety measures against these damages, it is necessary to understand the dynamic characteristics of an earthquake. The responses of RC buildings primarily depend on the low, intermediate, and high FC under GMs., as presented in table 1. Across the World, the majority of the existing RC buildings in the seismic region do not meet the recent seismic code requirements as these are primarily designed for gravity loads only. These buildings are constructed with masonry infill walls. The existing structural design practice considers the unreinforced brick or concrete blocks masonry infill walls as a non-structural element. Additionally, infill is commonly neglected in the structural analysis; thereby, stiffness contributions are being ignored, resulting in an evaluation of longer natural periods and less stiffness estimation. However, infill resists a certain amount of lateral forces during an earthquake [2].

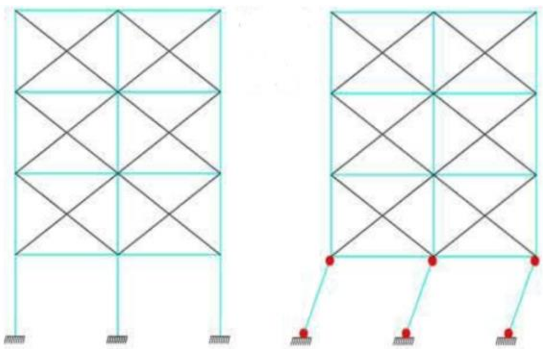

Fig1: Soft storey building failure mechanism

Government, local municipal rules, and public demand enforce compulsion on the builders to provide parking space at the ground storey. This construction practice leads to the soft open ground storey, as shown in Fig 1. These storeys in the buildings attract large earthquake excitations and display more horizontal deflections than upper storeys, causing severe structural elements or complete collapse. It is very important to model the unreinforced masonry (URM) infill precisely to obtain accurate EDPs. In the present work, infills are modeled as pin-jointed equivalent diagonal strut as proposed in [3-5] shown in Fig. 2.

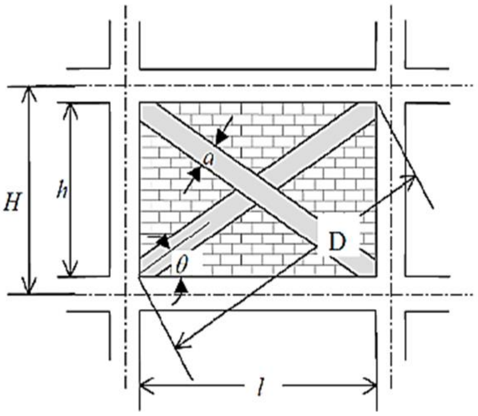

Fig 2: Equivalent diagonal strut

The effect of earthquake FC on the cantilever's seismic behavior retaining wall was evaluated [6]. The seismic behavior of partially filled rigid rectangular tank with bottom mounted submerged block under low, intermediate, and high FC GMs was studied [7]. URM infill's influence is considered and studied as non-structural elements in most countries [1]. URM infill, along with beams and columns, has a foremost contribution to buildings' seismic behavior during an earthquake. Moreover, the building's mode shape depends on the distribution of lateral storey stiffness and the height of the building. Improvement of lateral storey stiffness is reliant on the distribution of URM in each storey. The open ground storey has lesser lateral stiffness than the above storeys. Accordingly, open ground storey influences the mode shape of the building. Thus, the mode shape attained with lateral stiffness contribution of URM infill walls differs considerably than without URM. The vertically irregular RC buildings known as open ground storey buildings were examined as in [8]. Nonlinear dynamic analyses of RC frames subjected to a number of GMs scaled for different PGA were performed to estimate the EDPs. They concluded that component level EDP based fragility is effective in predicting the actual damage in buildings.

The effect of FC in the range 1.2 to 1.6 was explored on regular and irregular low, mid, and high rise RC buildings for six earthquake GMs records as in [9]. Three, six, and twenty storey RC buildings were modeled and analyzed in STAAD Pro. They concluded that both regular and irregular low rise RC buildings are affected significantly for low to intermediate FC GMs. Furthermore, six stories RC building demonstrates maximum storey displacement to low FC earthquake ground motion. The seismic performance of a G+9 storied masonry infill RC frame building was evaluated by linear and nonlinear dynamic analysis using ETABS as in [10]. The response work, spectrum pertaining to the specifications specified in the IS 1893 (Part 1): 2016 [11] and LTHA, were considered for the analysis. The author concluded that a full infill frame shows better seismic behavior than bare and soft storey frames. A. Regular 3D three and six storey RC buildings with six GMs of low, intermediate, and high FCs having equal duration and PGA were studied [12]. The RC buildings were modeled LTHA was performed in SAP 2000. The response of buildings in terms of storey displacement and base shear was established. They concluded that low and intermediate FC GMs have a significant effect on regular RC buildings. However, high FC GMs have very less effect on responses of the regular RC buildings.

Ten storey regular and vertically irregular RC buildings were analyzed by the response spectrum and THA in ETABS 2015, as investigated in [13]. It is concluded from the analysis that low FC earthquakes do not impact the response of vertically irregular buildings. Furthermore, vertically irregular buildings in regions of intermediate and high FCs earthquakes in earthquake-prone areas should be avoided if possible. Otherwise, beam-column joints must be designed considering ductility as per code provisions of respective countries. Two to five storey regular RC buildings are studied and focused on the effect of varying FC GMs in low-rise RC buildings keeping the PGA and duration constant as in [14]. Seven GMs having individual predominant frequency are selected, and ETABS carried out LTHA. The results obtained reveal that the building's response increases with an increase in FC of the GMs to a certain point and decreases. The sensitivity of the FC increases with an increase in the number of storey.

The bare, vertically irregular, and fully infill frame RC buildings were considered in [15]. According to Smith and Hendry formula, the infill was modeled as a diagonal strut approach (adopted by the Canadian Standard (CSAS304.1-04)). The static analysis as per Bangladesh code procedures, response spectrum, and THA were carried on buildings. It is observed that the response of building structures shows that there is a significant contribution of infill in the characterization of their seismic behavior. Therefore, the variation of displacement in successive floors is little in regularly infill structure than in irregularly infill structure. Fully infill configuration will give more lateral strength to the structure. Seismic assessments of five RC frame building models considering the stiffness effect of brick masonry infill were executed [16]. Structural responses in terms of fundamental natural periods, storey displacements, and base shear were determined. It is concluded that the calculation of earthquake forces by treating RC frames as ordinary moment-resisting frames without regard to infill stiffness leads to underestimating base shear. The configuration of infill walls in the parking frame changes the frame's behavior; therefore, it is important for the structural systems selected to be thoroughly investigated and well understood, particularly the soft ground floor. The performances of masonry infill buildings were considerably superior to that of bare and soft storey frames.

Floor acceleration demands were estimated in multi-storey buildings subjected to earthquakes as a parametric study [17]. It is reported that the fundamental period of the structure and the lateral stiffness ratio significantly change acceleration demands in buildings. Spectral amplifications around the first mode of the structure decrease as the fundamental vibration period increases and increases as the lateral stiffness ratio increases. The effective way of allocating viscous oil dampers to the storeys, which exhibit large inter-storey drifts, was investigated in [18]. It is concluded that large distribution of the maximum inter-storey velocities was observed in lower storeys in super high-rise buildings, which greatly influences viscous oil dampers' effective location. The buildings with fluid viscous dampers (FVDs) as a retrofitting technique to reduce inter-storey drifts, floor accelerations, and sensitive structural damage was proposed [19]. Peak inter-storey drifts and velocities developed under seismic forces in frame structures equipped with inter storey viscous dampers were studied as in [20]. The main author aimed to assess the efficiency of simple logical predictions, which could be valuable for proficient engineers, particularly in the preliminary design phase.

II. BUILDING DESCRIPTION

The building models' geometry and material properties considered for the analyses in this work are presented in Table 1. The plan and elevation of building models are shown in Fig. 3 to 6.

Table I
Geometrical and Material Properties of Building Models

Sl. No.	Particulars	Data
1	C/S of beam and columns	380 X 380 mm
2	Slab thickness	120 mm
3	Wall thickness	250 mm
4	Parapet wall thickness	100 mm
5	Grade of concrete	M25
6	Grade of steel	Fe500
7	The density of Brick infill	20 kN/m^3
8	The density of concrete block infill	21 kN/m^3
9	E for brick infill [21]	3285.9 MPa
10	E for concrete block infill [22]	6600 MPa
11	Poisson's ratio of both infill	0.2
12	Live load	3 kN/m^2
13	Roof live load	2 kN/m^2
14	Floor finish	1 kN/m^2
15	Wall load (UDL-Brick)	12.1 kN/m
16	Wall load (UDL-Concrete block)	12.7 kN/m
17	Parapet (UDL-Brick)	2 kN/m
18	Parapet (UDL-Concrete block)	2.1 kN/m
19	Frame	OMRF
20	Seismic zone	III
21	Zone factor (Z)	0.16
22	Soil	Medium
23	Response reduction factor (R)	3
24	Importance factor	1
25	Width of the diagonal strut (Brick)	1.221 m
26	Width of diagonal strut (Concrete)	1.026 m

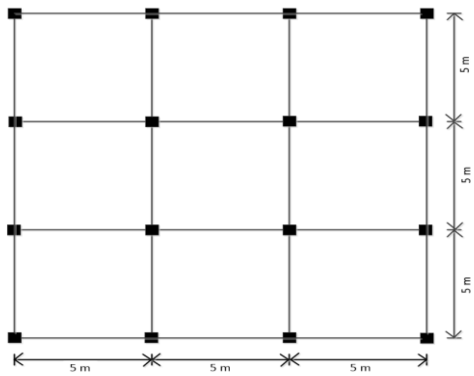

Fig 3: Plan of the building

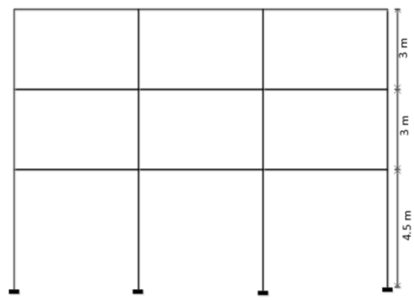

Fig 4: Elevation of the bare frame building model

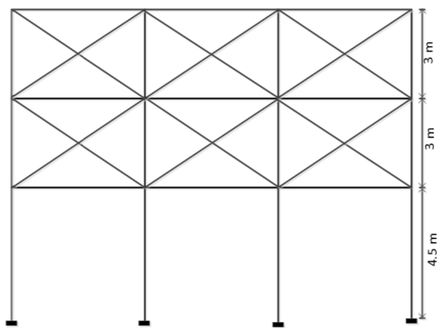

Fig 5: Elevation of the soft storey building model

Roof live load is not considered for calculating the seismic weight of the building [11].

III. METHOD OF SEISMIC ANALYSIS

A. Equivalent Static Analysis (ESA)

ESA [11] does not require dynamic analysis; however, it accounts for the dynamics of the building based on IS 1893 (Part 1): 2016 [11]. Design base shear calculated for all the building floors is distributed as parabolic variation throughout the height of the building.

B. Response Spectrum Analysis (RSA)

RSA [11] is the linear dynamic analysis and incorporates the peak response of structure during an earthquake obtained directly from the earthquake response and is reasonably accurate for structural design applications.

Time History Analysis (THA)

THA is the study of the dynamic response of the structure at every addition of time when its base is exposed to particular ground motion. Static techniques are applicable when higher mode effects are not important. This is, for the most part, valid for short and regular structures. The structure is modeled as a multi-degree of freedom (MDOF) classification with a linear elastic stiffness matrix and an equivalent viscous damping matrix in the linear dynamic method. The seismic loading is modeled employing THA. The displacements and internal forces are established by linear elastic analysis. The linear dynamic procedure's significant point as for linear static procedure is that the higher modes could be taken into account.

IV. FREQUENCY CONTENT

It is defined as the ratio between PGA in 'g' to PGV in m/s. Earthquake GMs are categorized into low, intermediate, and high FC GMs.

- Low - FC < 0.8
- Intermediate - FC 0.8 to 1.2
- High - FC > 1.2

This study considers nine earthquake ground motion records with FC shown in Table 2. The ground motion records are taken from the SeismoSignal software database and COSMOS database. All the records are scaled to 0.3 g with equal PGA, PGV, and FC for earthquakes duration of 40 seconds using SeismoSignal software.

Table II
Classification of ground motion records

Sl. No	Earthquake	PGA (g)	PGV (m/s)	FC	Classification
1	Hectormine, USA, 1999	0.3	0.659	0.454	Low
2	Loma Prieta, USA,1989	0.3	0.364	0.822	Intermediate
3	El-Centro, USA, 1940	0.3	0.299	1	Intermediate
4	Kobe, Japan,1991	0.3	0.241	1.245	High
5	Bhuj, India, 2001	0.3	0.182	1.643	High
6	Chi Chi, Taiwan, 1999	0.3	0.171	1.676	High
7	Uttarakashi, India, 1991	0.3	0.171	1.756	High
8	Trinidad, USA, 1983	0.3	0.131	2.28	High
9	Coalinga, USA, 1983	0.3	0.091	3.29	High

V. METHODOLOGY

The RC buildings considered for the evaluation are modeled as,

The model I - Building has no brick walls, and the building is modeled as the bare frame. However, masses of the walls are included.

Model II - The building has no brick walls in the first storey and unreinforced bricks masonry infill wall in the upper stories. Stiffness and masses of the walls are considered.

Model III - The building has no concrete block walls, and the building is modeled as a bare frame. However, masses of the walls are included.

Model IV - The building has no concrete block walls in the first storey, and unreinforced concrete blocks masonry infill walls in the upper stories. Stiffness and masses of the walls are considered.

VI. RESULTS AND DISCUSSIONS

The present work focuses on determining the natural periods, base shear, roof displacements, storey drift, storey velocity, and storey acceleration of models to evaluate the responses under varying FC of nine GMs.

Natural Period

The natural period of models by Eigen value analysis are shown in Table 3. It is seen that natural periods are shorter for masonry infill frame buildings than those obtained in bare frame buildings. These results indicate that the stiffness of model II and IV are increased compared to models I and III with masonry infill. Therefore, buildings with masonry infill in the second and third storey are further capable of sustaining earthquakes than bare frame models.

Table III
Natural periods in seconds of building models

Models	Bare frame	SOGS	% decrease
The model I & II	0.82	0.68	-20.53
Model III & IV	0.83	0.65	-26.56

Base shear

Base shear of models corresponding to all earthquakes GMs under varying FC is displayed in Fig. 6 and 7.

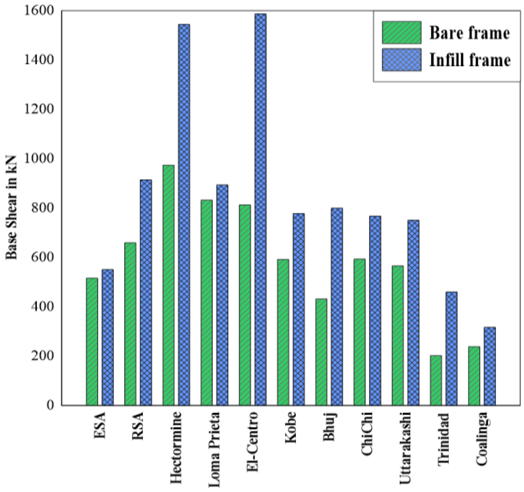

Fig 6: Base shear of Model I and II

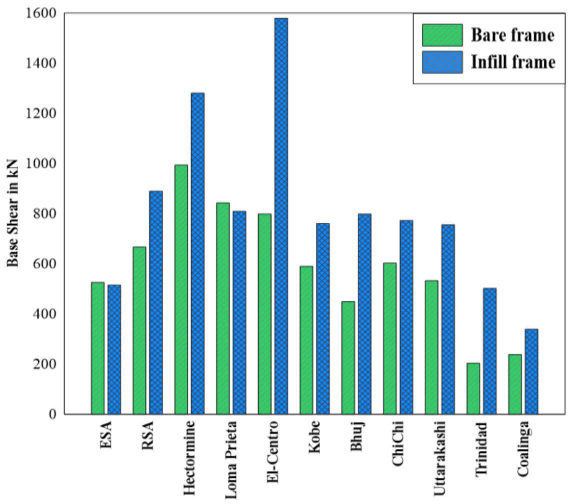

Fig 7: Base shear of Model III and IV

It is seen from the magnitudes of base shear for ESA, RSA, and nine earthquakes that intermediate FC earthquake GMs enhance the base shear in models than those obtained by high FC earthquake GMs. Thus, intermediate earthquakes demonstrate that the buildings are stiffer and can absorb more earthquake forces than low and high FC GMs.

Roof Displacement

Roof displacements of models to earthquake GMs for varying FC are shown in Fig. 8 - 11. It is noticed that lateral displacements in all the model floors by intermediate FC earthquake GMs are more than the higher FC earthquake GMs. These results demonstrate flexible performance in the buildings subjected to FC equal or lesser than 1.2 earthquake GMs. Lateral displacements throughout the height of mainly the SOGS models are reduced to a great extent at second and third storey floors and are marginally equal or more than at open ground slab movements by all earthquakes except for Hectormine LTHA. This result reveals that more seismic forces were taken by masonry infill, reducing the likely increase in lateral displacements and fragility for earthquake shaking. Furthermore, the presence and consideration of masonry infill during analysis show that the lateral stiffness of stories above SOGS increase.

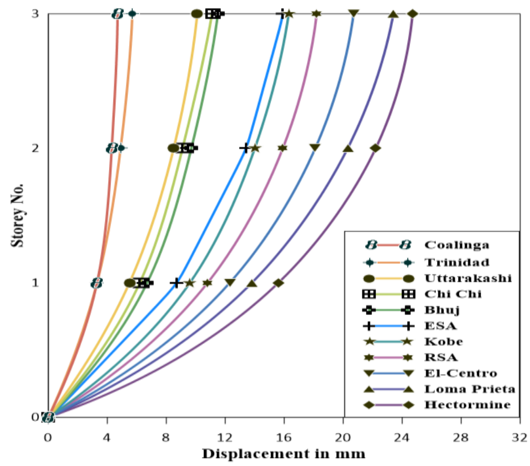

Fig 8: Roof displacements of Model I

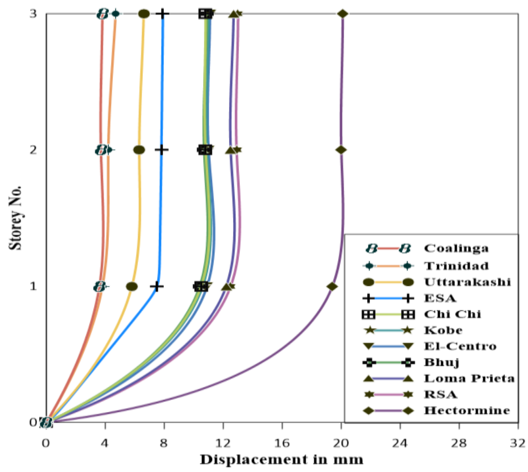

Fig 9: Roof displacements of Model II

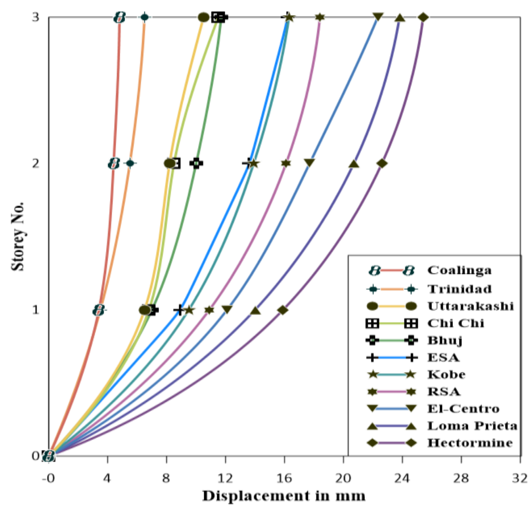

Fig 10: Roof displacements of Model III

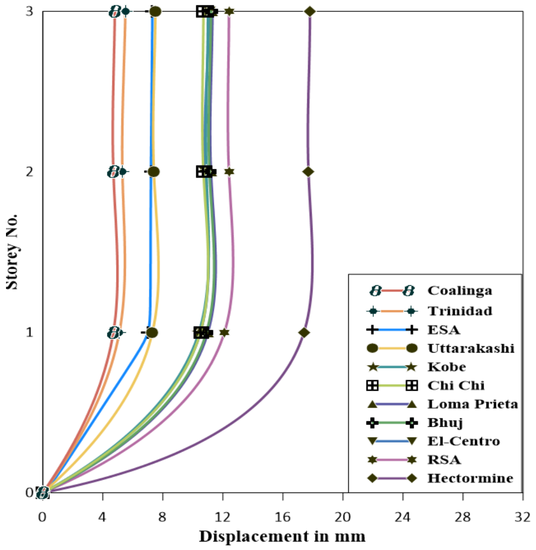

Fig 11: Roof displacements of Model IV

Inter Storey Drift

It is seen from the Figs. 12 -15 that, the soft open ground floor experience greater storey drift than above floors for any FC earthquake GMs. El-Centro earthquake GMs display the storey drift at soft open ground slab with concrete masonry infill exceed the code limit of 0.004 times the storey height [11]. Additionally, the limit is as well in model II for the Hectormine earthquake. Inter storey drift from second to third storey slabs is reduced by masonry infill models for every FC earthquake GMs and, to a little extent, in bare frame models. These results greatly influence civil engineers for viscous oil dampers' location as retrofitting measures to reduce vulnerability on the first floor [18-20].

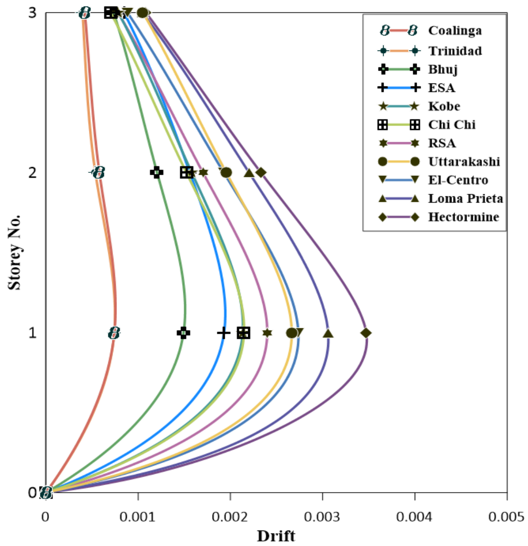

Fig 12: Inter storey drift of Model I

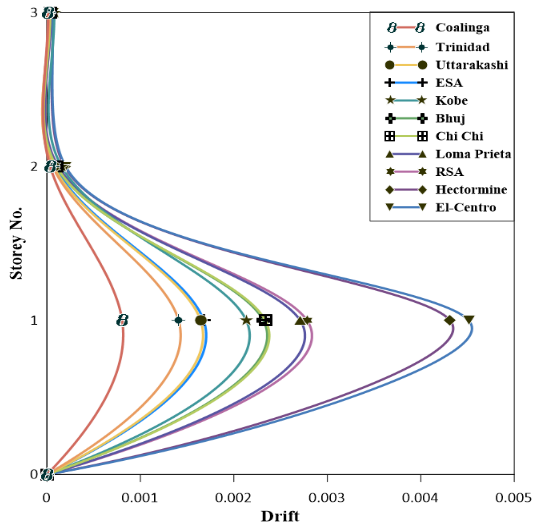

Fig 13: Inter storey drift of Model II

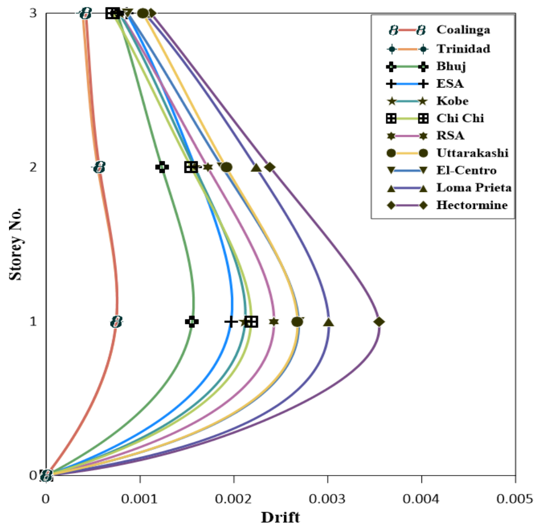

Fig 14: Inter storey drift of Model III

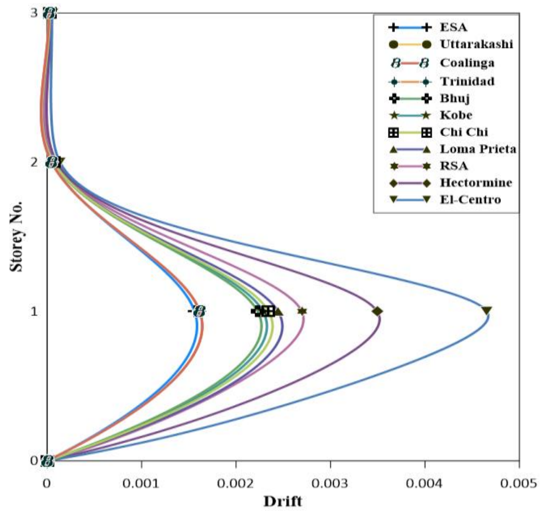

Fig 15: Inter storey drift of Model IV

Storey Velocities

Fig. 16-19 compares the first mode peak inter-storey velocity profiles for the building models obtained from the LTHA for varying FC earthquake GMs. Fig. 16 and 18 show the bare frame model's storey velocity increases nearly linear as the storey increases, excluding Coalinga and Trinidad high FC earthquakes. As seen in Fig. 17 and 19, soft open ground storey models display masonry infill in the second and third floor attract storey velocity and equal to first storey slab results. From the second storey to the building height in soft open ground storey models, inter storey velocity results are more or less constant.

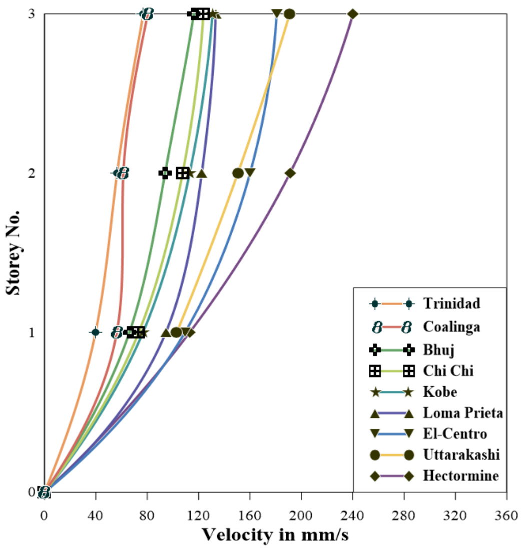

Fig 16: Storey velocity of Model I

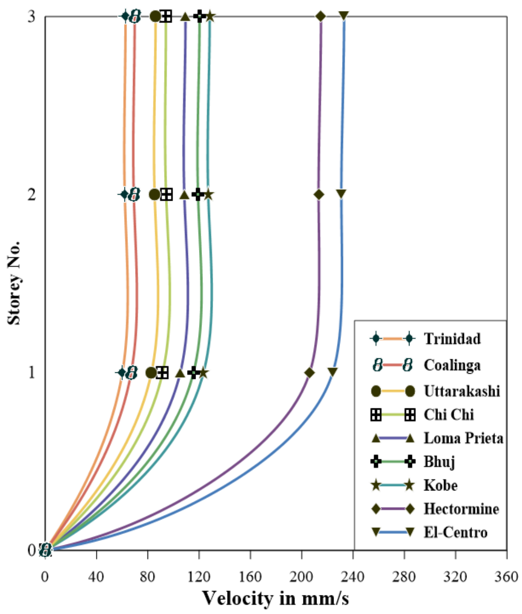

Fig 17: Storey velocity of Model II

Storey acceleration

Fig. 20-23 demonstrates that the increase in storey acceleration along the bare frame models' height is almost linear for intermediate and low FC earthquakes. Further, the second and third storey accelerations of models II and IV are equal to the first storey slab level acceleration results, respectively. Therefore, masonry infill in the above stories of SOGS absorbs storey acceleration, thereby reducing fragility to the second and third storey's structural frame elements.

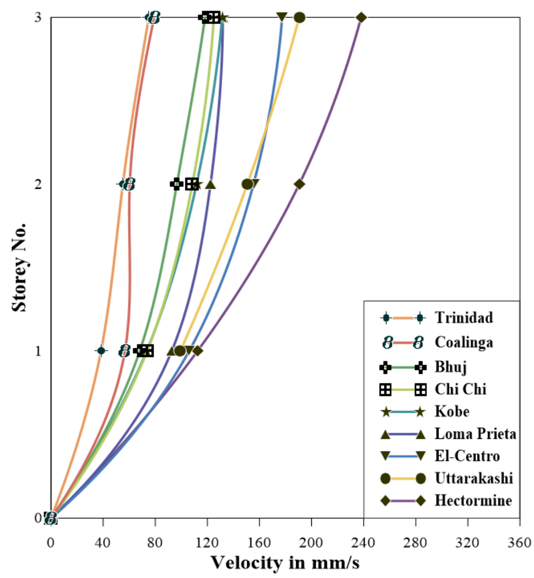

Fig 18: Storey velocity of Model III

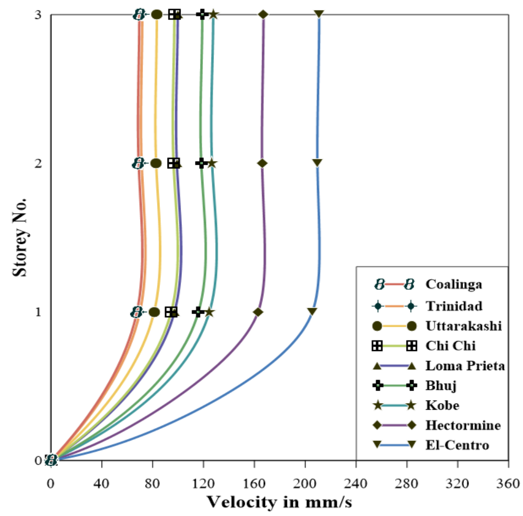

Fig 19: Storey velocity of Model IV

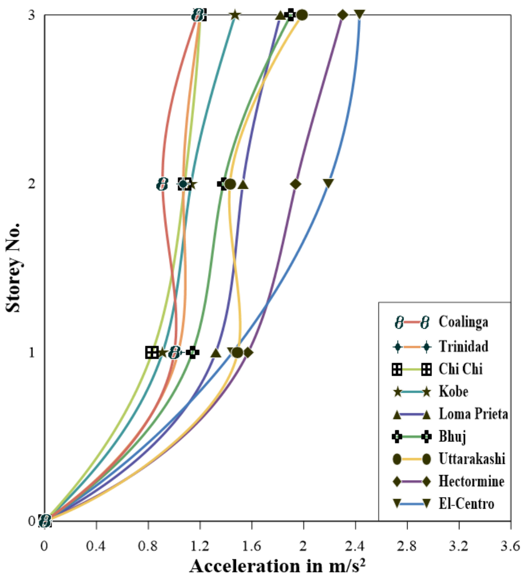

Fig 20: Storey acceleration of Model I

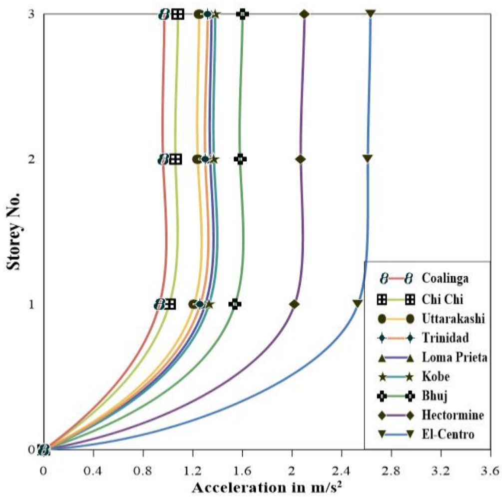

Fig 21: Storey acceleration of Model II

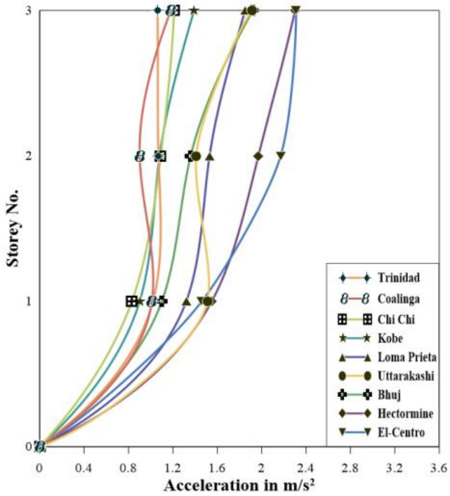

Fig 22: Storey acceleration of Model III

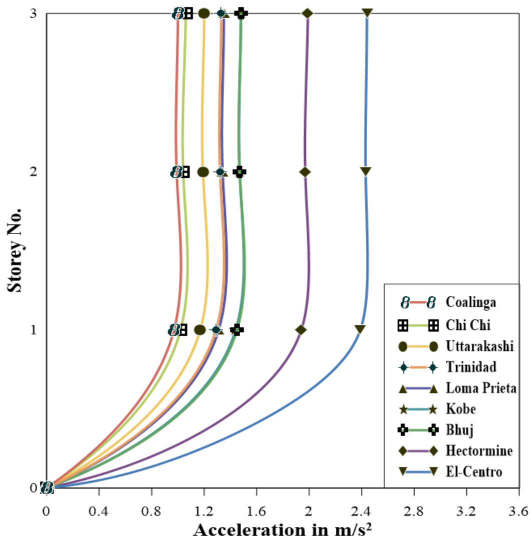

Fig 23: Storey acceleration of Model IV

Storey Stiffness

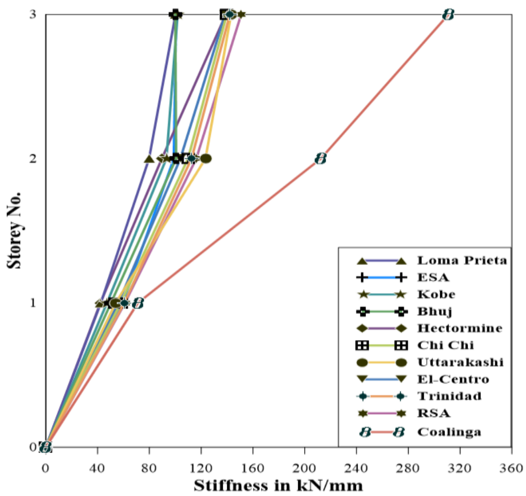

Fig 24: Storey stiffness of Model I

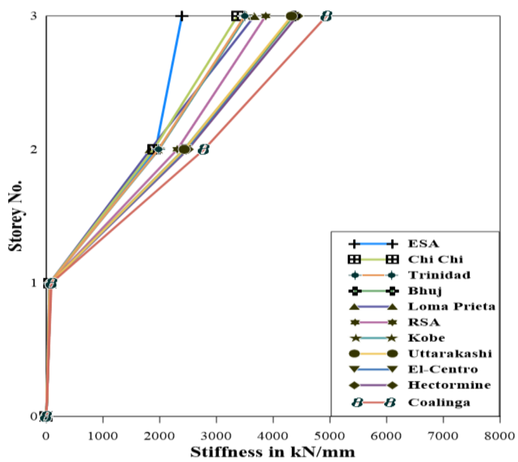

Fig 25: Storey stiffness of Model II

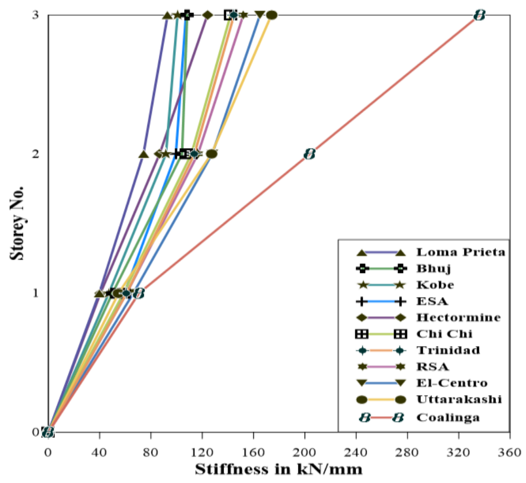

Fig 26: Storey stiffness of Model III

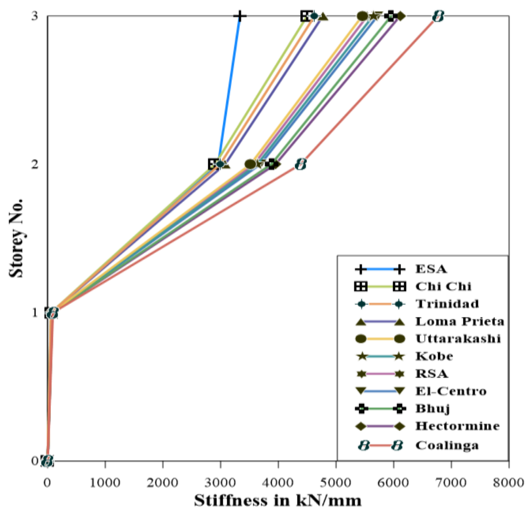

Fig 27: Storey stiffness of Model IV

Fig. 25 and 27 show that second and third storeys are stiffer due to the presence of masonry infill than bare frame models (Fig. 24 and 26). Thereby resulting vulnerability to earthquake vibrations and, therefore, implementation of viscous oil dampers as one of the retrofitting techniques at strategic locations is suggested in SOGS.

VII. CONCLUSIONS

The paper presents the study's major results focussed on the assessment of EDPs developed in the RC frame buildings. Further, the proposed study explores the effect of linear static, dynamic, and time history analyses for varying FC of earthquake GMs. The following are concluded from the current study:

1. EDPs responses for the similar models subjected to GMs of diverse FC vary considerably even though they have the same PGA and duration.

2. Constructions of buildings on soft and medium soil are to be avoided because building models' responses increase as the FC of GMs decreases.

3. Constructions of buildings without considering the stiffness of masonry infill are avoided as factual EDPs are not obtained.

4. EDPs responses on the first floor of SOGS RC buildings reveal that viscous oil dampers be installed in between exterior frame elements symmetrically as a retrofitting measure to reduce damage in the ground storey.

5. Civil engineers can employ bricks or concrete blocks as masonry infill in-between frame elements of three storey RC buildings since EDPs are nearly equal.

6. Stimulation by at least one earthquake GMs with LTHA lesser than intermediate FC must be included in local building laws and stipulated by the civil engineers to build the low rise RC buildings constructed in an earthquake-prone area.

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