ANALYSIS OF BUILDINGS IN HILLY TERRAIN UNDER MULTIPLE HAZARDS

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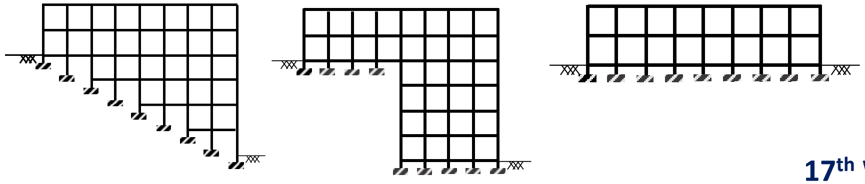
Typical Structural Configuration of Hilly Buildings

- Buildings in hilly region are often constructed on or near the hill slope due to unavailability of adequate flat land.
- The hillside buildings where foundations follow the natural slope of the ground, known as step-back (SB) buildings.
- In case of steep slope, buildings with foundation at two different levels can be observed, known as split foundation (SF) buildings.
- The constraints posed by topography lead to irregularities in both plan and elevation, resulting into complex behavior of buildings in the hilly region under earthquake excitation as compared to the buildings on flat land (FL).



(a)Step-back (SB) Building

(b) Split foundation (SF) Building

Objective

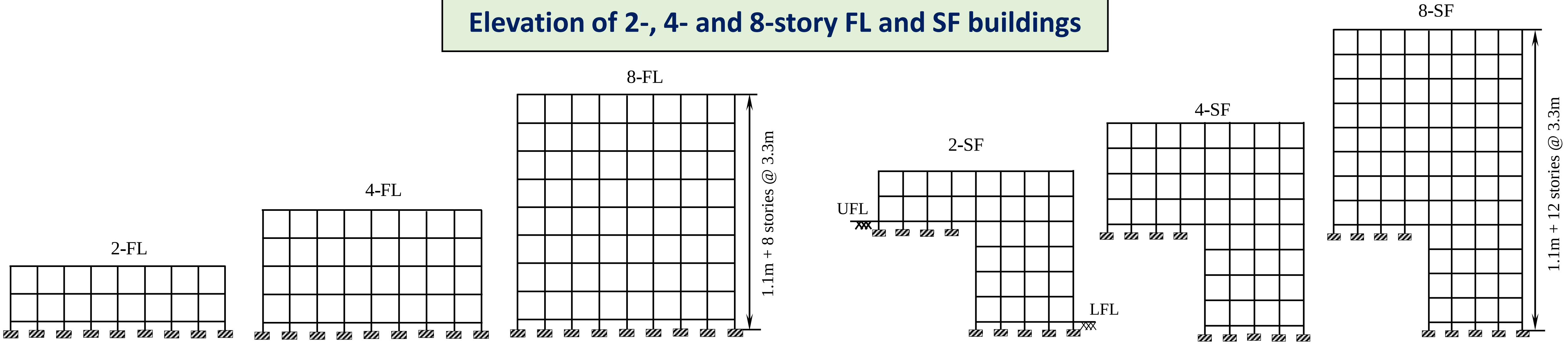
i. To investigate the effectiveness of base isolation system for buildings in hilly region and examine their performance under multiple hazards like earthquake, wind and blast.

ii. To carry out a parametric studies to assess the influence of characteristic strength of lead-rubber bearing (NZ system) on the peak responses of the hilly buildings.

Modelling of Base-isolated Buildings

- Three-dimensional bare frame model of split-foundation (SF) and flat-land (FL) buildings are modelled using beam element in SAP2000 (2021).
- The story ratios considered for the split foundation models are 0.5, 1 and 2 keeping the constant 4-stories below the uppermost foundation level (UFL).
- Building models are considered as special moment-resisting frames according to IS 1893 (2016) Part 1 for Seismic Zone-V and soil type as rock and hard soil.

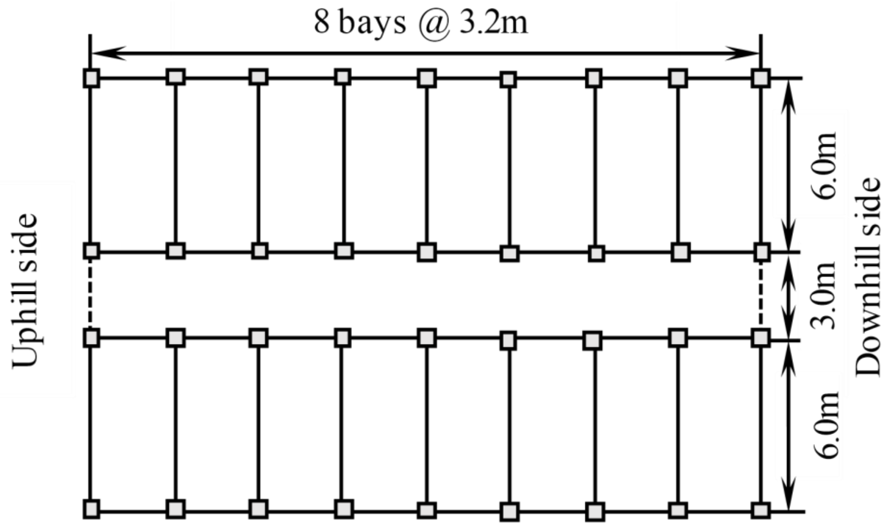
Elevation of 2-, 4- and 8-story FL and SF buildings



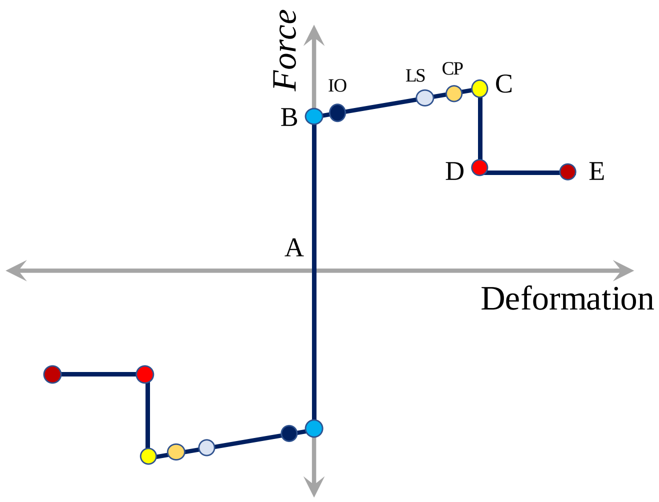
Modelling of Base-isolated Buildings

- The material nonlinearity using the lumped plasticity model is also considered in the numerical models.
- The plastic hinges are applied at the start and end of the beams (M3 type) and columns (P-M2-M3 type) as per ASCE 41 (2013).
- The present study considers the P-delta effects in the structural analysis to incorporate the geometric nonlinearity.

Generic plan of FL and SF building



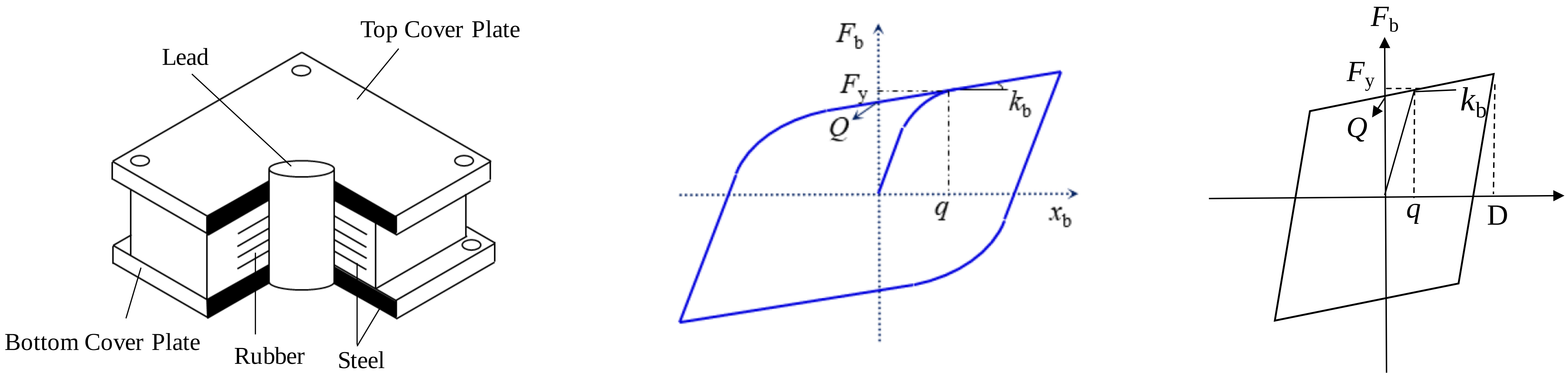
Typical plastic hinge behavior



Structural members are designed to withstand the dead load, live load and earthquake load (IS 1893 Part-1 2016). Dead loads and live loads on the buildings are considered according to IS 875 (1987) Part 1 and Part 2, respectively.

Modelling of Base-isolated Buildings

- In the present study, the lead-rubber bearing (NZ-system) is considered at the base of each column for all the building models.
- The natural period (T_b), characteristic strength (Q) and yield displacement (q) are used to characterized the isolator.
- The isolation system is modelled using link element (Plastic-Wen) in SAP2000v20 (2021)



Schematic diagram of lead rubber bearing and idealized force –deformation behavior

Multi-hazard Loading on Base-isolated Stepped Buildings

Earthquake Ground Motions

- Seven earthquake records are selected from PEER database following the FEMA P695 (2009) criteria.

RSN	Earthquake Name	Year	Station Name	M_w	PGA (g)	R_{jb} (km)
71	San Fernando	1971	Lake Hughes #12	6.61	0.38	13.99
162	Imperial Valley-06	1979	Calexico Fire Station	6.53	0.28	10.45
164	Imperial Valley-06	1979	Cerro Prieto	6.53	0.17	15.19
289	Irpinia Italy-01	1980	Calitri	6.90	0.14	13.34
313	Corinth Greece	1981	Corinth	6.60	0.30	10.27
587	New Zealand-02	1987	Matahina Dam	6.60	0.28	16.09
719	Superstition Hills-02	1987	Brawley Airport	6.54	0.14	17.03

R_{jb} - Joyner-Boore distance to rupture plane; M_w - Moment magnitude of earthquake

Multi-hazard Loading on Base-isolated Stepped Buildings

Wind load

- The mathematical expression of design wind speed (V_z) is given by

$$V_z = V_b k_1 k_1 k_3 k_4$$

here, V_b is the basic wind speed and taken as 39m/sec as specified in IS 875 (2015) part 3.

- The design wind pressure (p_d) is defined as

$$p_d = K_d K_a K_c p_z$$

where $p_z = 0.6{V_z}^2$ is the wind pressure at height z.

- Wind load on the individual members acting in the direction normal to the structural member can be calculated by

$$F = \left(C_{pe} - C_{pi}\right) A p_d$$

here, C_{pe} and C_{pi} are the external and internal wind pressure coefficient; *A* is the tributary area.

k_1 = Risk coefficient
k_2 = Terrain roughness and height factor
k_3 = Topography factor
k_4 = Importance factor for the cyclonic region

K_d = Wind directionality factor
K_a = Area averaging factor
K_c = Combination factor

The value of internal pressure coefficient is considered as ±0.05 considering 5 to 20% opening in the building models.

Multi-hazard Loading on Base-isolated Stepped Buildings

Blast load

- The profile of the blast wave at any time instant is described by the modified Friedlander equation, as:

$$P(t) = P_0 + P_{pos}\left(1 - \frac{t}{t_{pos}}\right)e^{-bt/t_{pos}}$$

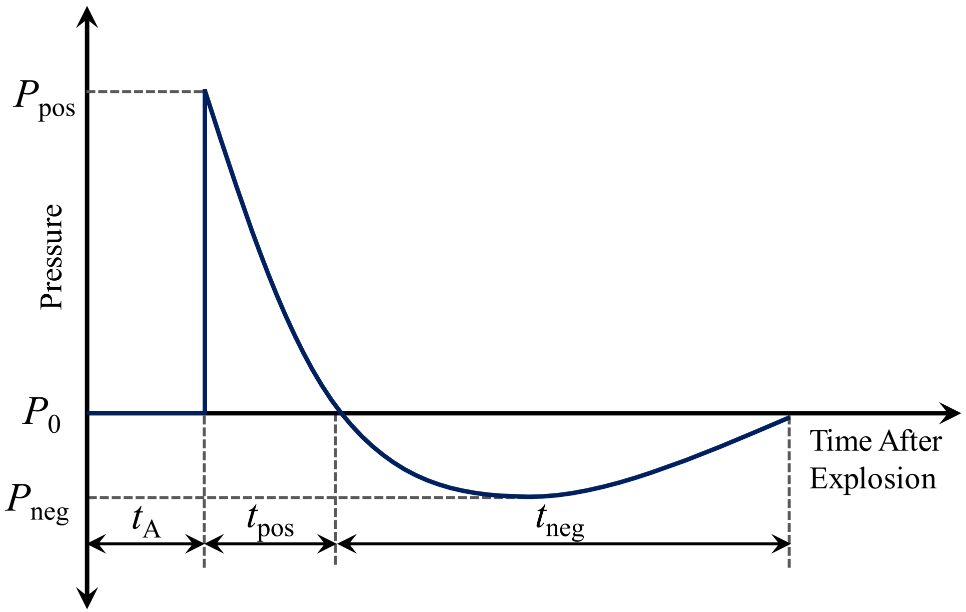
- where t is measured after arrival time t_A, and b describes the decay of wave as given in the following equation.

$$b = Z^2 - 3.7Z + 4.2$$

- The term Z is a scaled distance (m/kg$^{1/3}$) and can be calculated as

$$Z = R/W^{1/3}$$

here, R is the radial distance in meter from center of detonation to the point of consideration, and W is the equivalent weight of the trinitrotoluene (TNT) explosive in kilograms .



Here, P_{pos} is peak incident pressure, P_t is blast pressure at any time t, t_A is the arrival time , t_{pos} & t_{neg} are the duration of positive phase and negative phase of the blast wave.

Blast load

- The peak incident pressure can be calculated as follows (Kinney and Graham 1985):

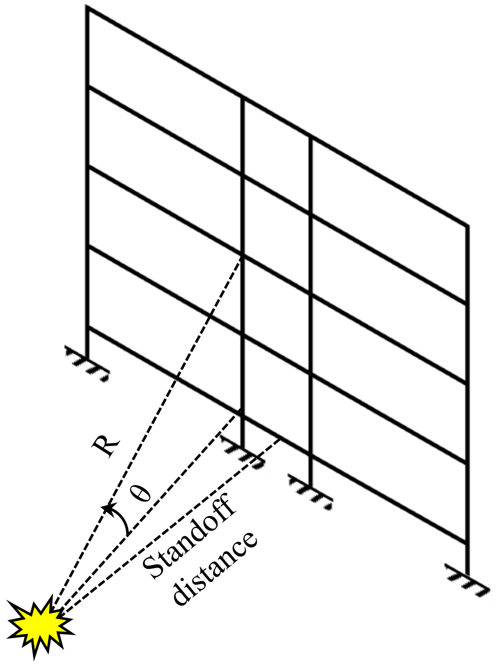
$$P_{pos} = \frac{P_0 \times 808 \times \left[1 + \left(\frac{Z}{4.5}\right)^2\right]}{\sqrt{\left[1+\left(\frac{Z}{0.048}\right)^2\right] \times \left[1+\left(\frac{Z}{0.32}\right)^2\right] \times \left[1+\left(\frac{Z}{1.35}\right)^2\right]}} \text{ (bar)}$$

- Here, P_0 = 1 bar is the ambient atmospheric pressure.

- The peak reflected pressure for a detonation can be calculated as follows:

$$P_{ref} = C_r P_{pos}$$

$$F = AP_{ref}$$



For a given value of P_{pos} and θ, the value of coefficient of reflection (C_r) can be obtained from Unified Facilities Criteria UFC 3-340-02 (UFC 2008).

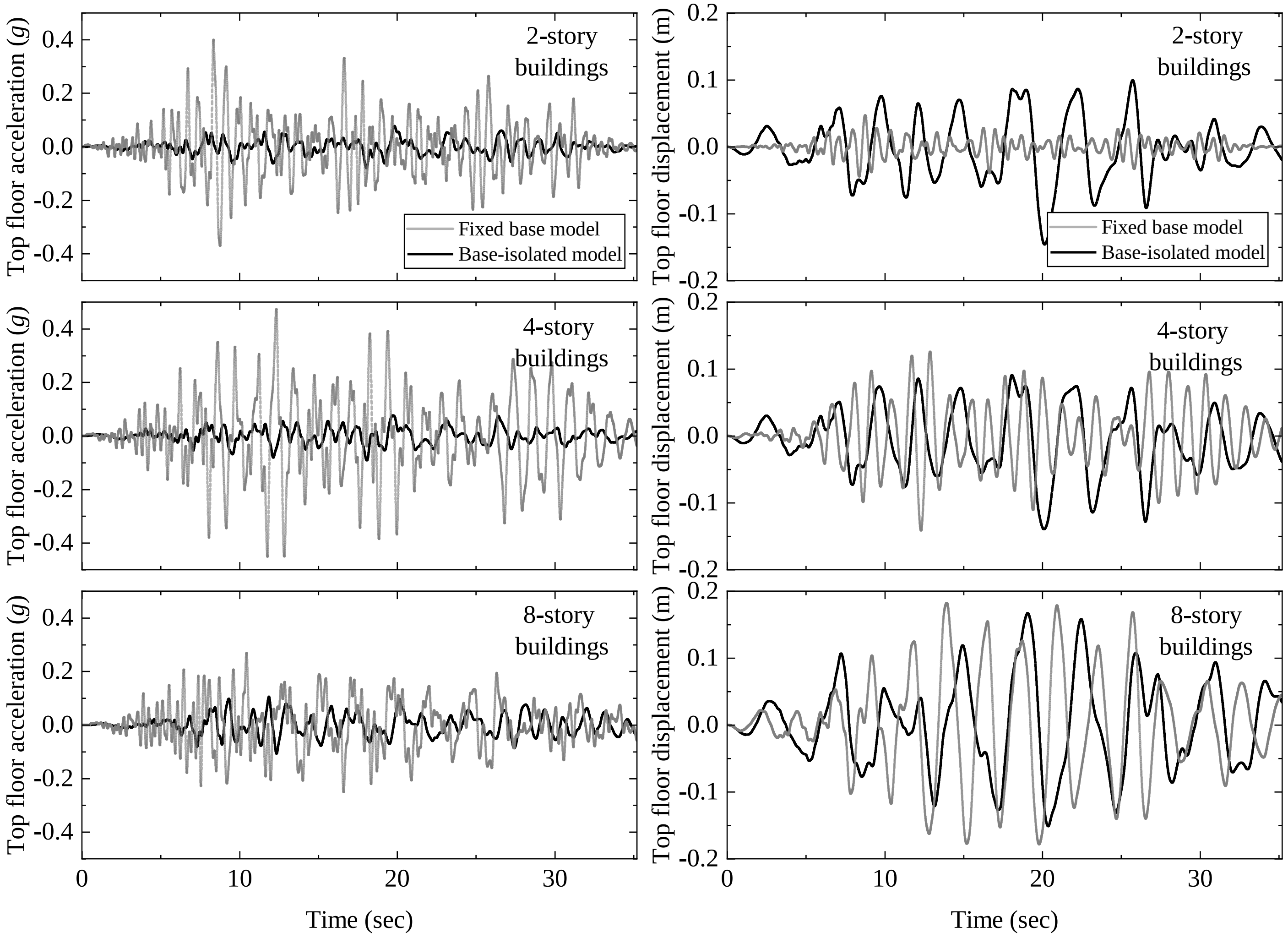
Response Analyses under Multiple Hazards

- The numerical investigations of hilly buildings under multiple hazards namely earthquake, wind and blast load were carried out.

- The nonlinear time history analysis (for earthquake load case) and nonlinear static analyses (for wind and blast load case) of the buildings are performed in structural analysis software SAP2000v20 (2021).

- The parametric studies are carried out to study the effect of isolation parameters on response quantities such as peak floor acceleration (PFA), inter-story drift ratio (IDR) and isolator level displacement of the base-isolated buildings.

Response of SF Buildings under Earthquake Excitation



Time histories of top floor acceleration and top floor displacement for SF buildings mounted on NZ System under Irpinia Italy-01 (1980) earthquake, recorded at Calitri station.

- The base-isolated building exhibits a significant reduction in the peak floor acceleration as compared to the fixed base building model.
- However, it can also be observed that the top floor displacement is more for base-isolated 2-story SF building as compared to its fixed base model.

Response of SF Buildings under Earthquake Excitation

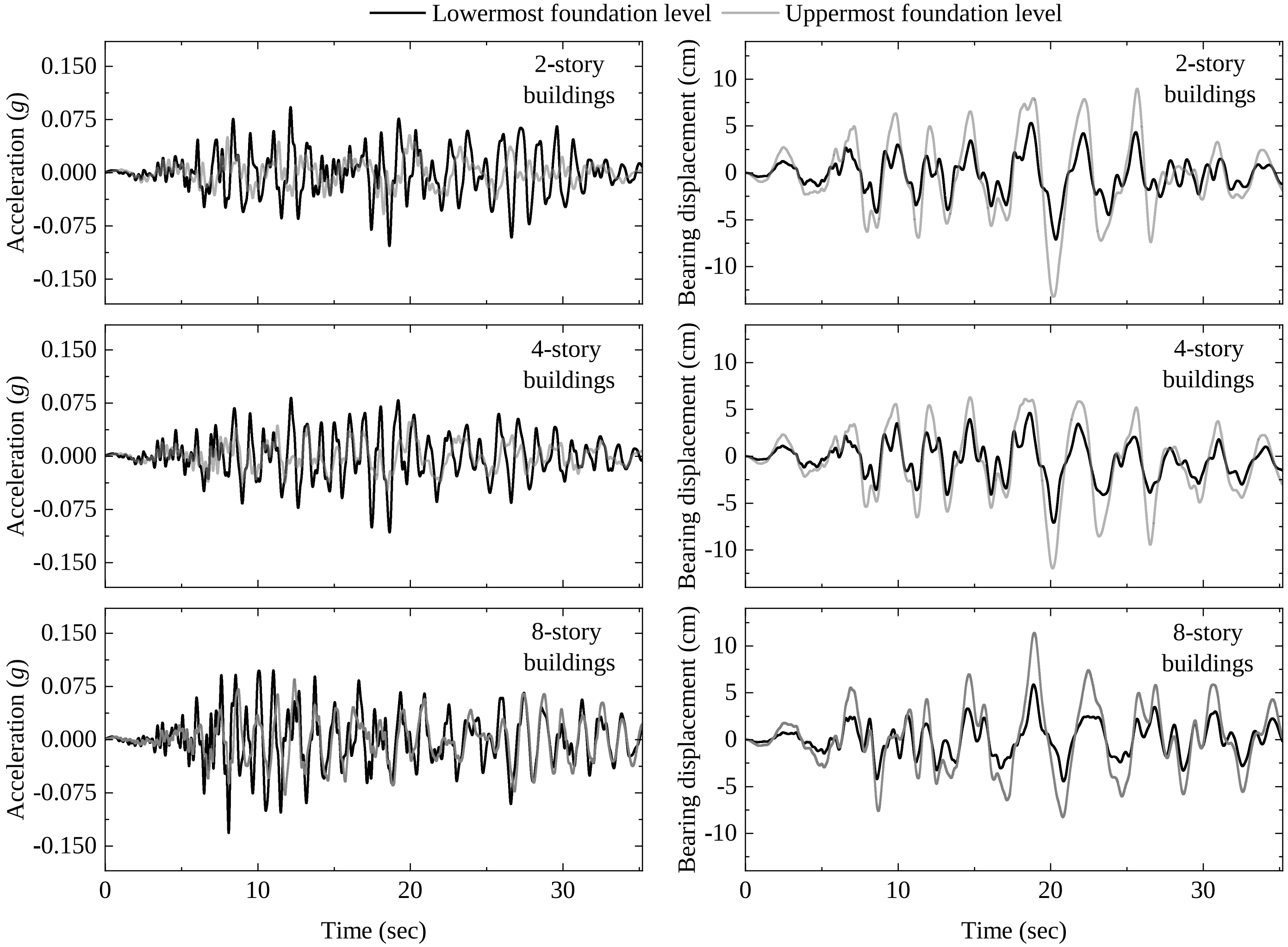
Table 1. Median values of isolator level displacement under various earthquakes

Type	Bearing displacement in cm					
	$Q/W = 0.05$		$Q/W = 0.075$		$Q/W = 0.10$	
	LFL	UFL	LFL	UFL	LFL	UFL
2 SF	4.54	9.03	4.54 (0.00)	8.59 (4.83)	4.05 (10.77)	8.07 (6.03)
4 SF	4.09	7.29	3.56 (12.96)	6.57 (9.76)	3.01 (15.21)	5.86 (10.92)
8 SF	3.98	7.92	3.53 (11.27)	7.71 (2.58)	3.11 (12.13)	7.34 (4.90)

Note: The percentage decrease in bearing displacement at the same level with increase in characteristic strength is presented within parenthesis.

- Isolator level displacement is observed to be higher at uppermost foundation level compared to the isolator at lowermost foundation level.

Response of SF Buildings under Earthquake Excitation



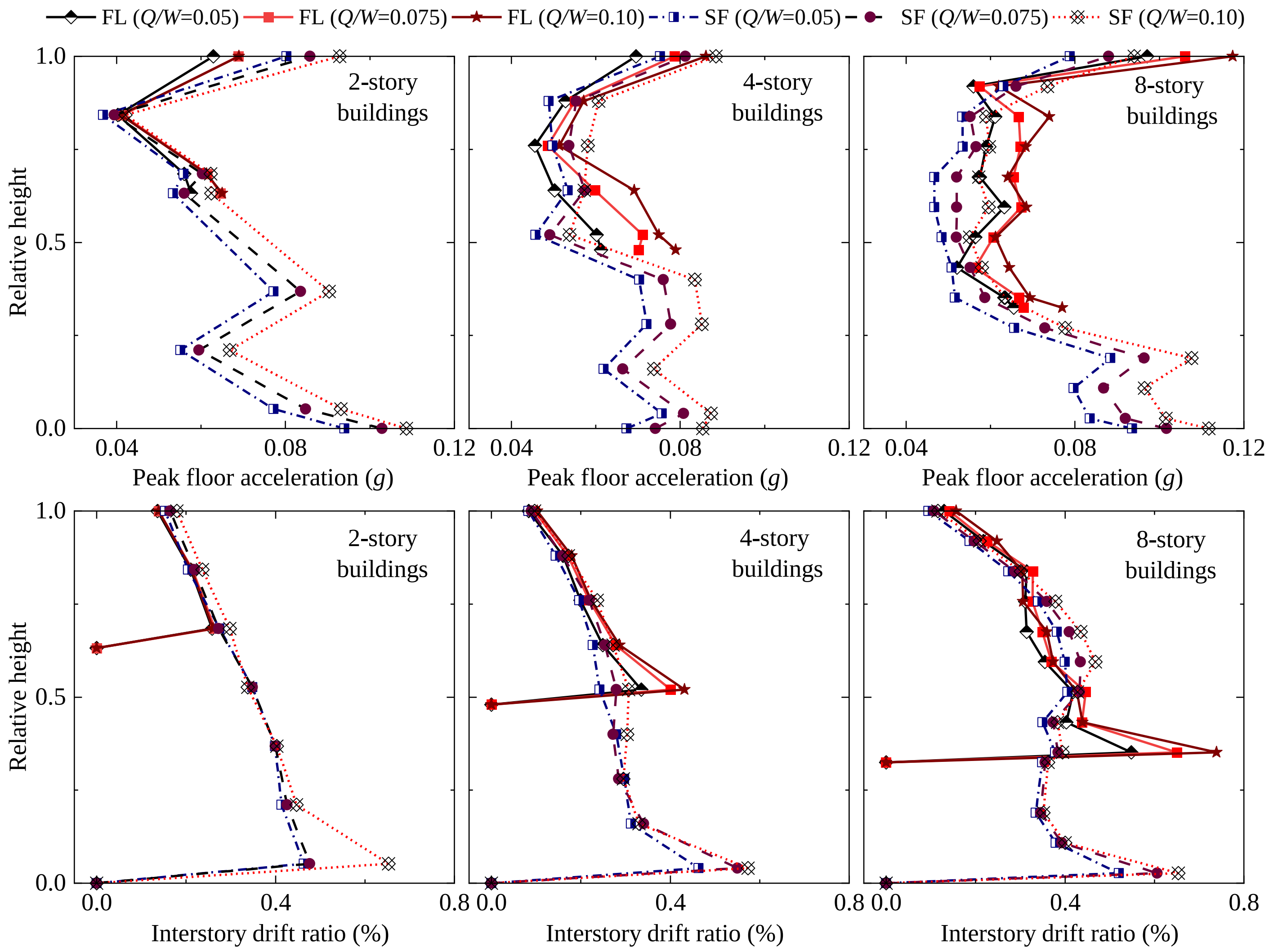
Time histories of isolator level acceleration and bearing displacement for base-isolated SF buildings mounted on NZ-system under Irpinia Italy-01 (1980) earthquake, recorded at Calitri station.

- The arrival time of peak values of both isolator level acceleration and bearing displacement is observed to be almost same.
- The isolator level acceleration at LFL is more than that of isolator at UFL, whereas the isolator level displacement at UFL is found to be more.

Response of SF and FL Buildings under Earthquake Excitation

- The response quantities PFA and IDR increase with increase in the characteristic strength of the isolator, and the similar pattern is observed when the number of stories increase.

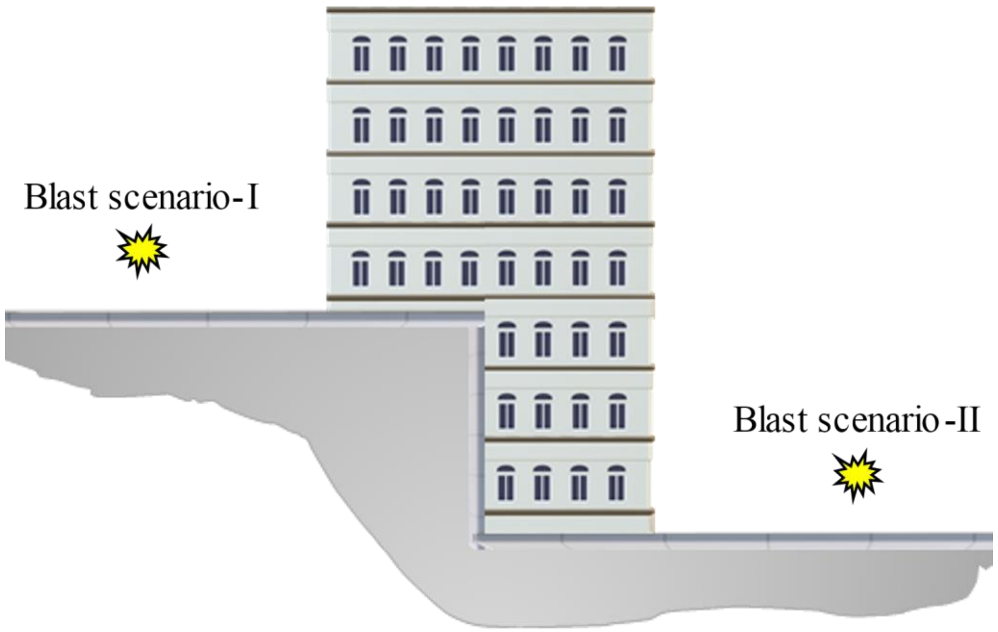
- The building portion below the uppermost foundation level in SF building experiences relatively higher inter-story drift as compared to the building portion above the uppermost foundation level.

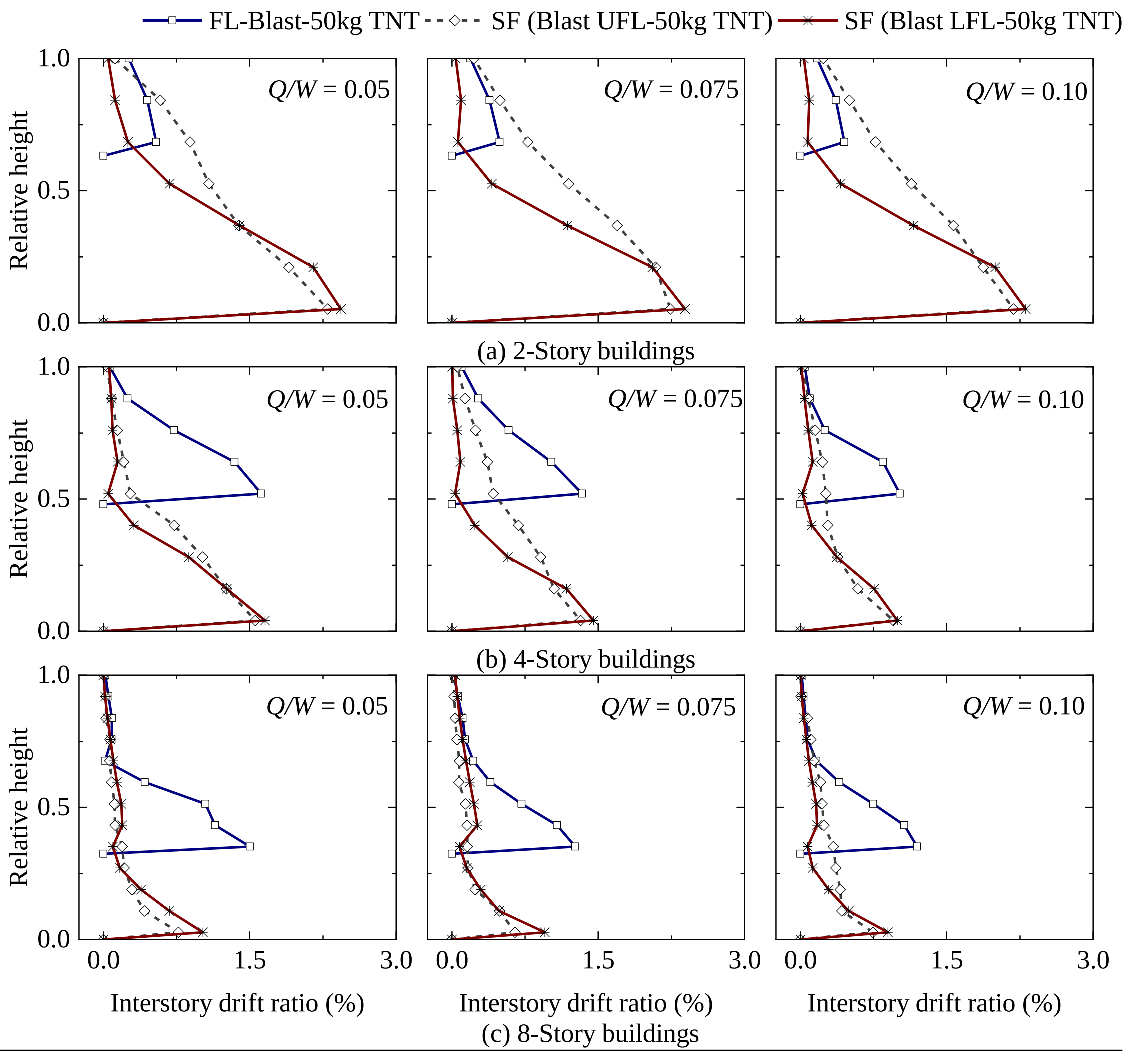


Median values of peak floor acceleration (PFA) and inter-story drift ratio (IDR) for flat land (FL) and split foundation (SF) base-isolated buildings.

Response of SF Buildings under Blast Load

Critical blast location ?





Inter-story drift ratio for flat land (FL) and split foundation (SF) building models under blast load of 50kg TNT at 15m standoff distance

Response of SF Buildings under Wind Load

Table 2. Peak values of inter-story drift ratio (%) under wind load (among all floors)

Type	Wind direction	Q/W \ Support	2-Story buildings			4-Story buildings			8-Story buildings		
			0.05	0.075	0.10	0.05	0.075	0.10	0.05	0.075	0.10
FL	-	Fixed	0.061			0.106			0.191		
SF	Downhill		0.052			0.104			0.256		
	Uphill		0.045			0.023			0.020		
FL	-	Base-isolated	0.131	0.130	0.130	0.161	0.161	0.160	0.351	0.348	0.346
SF	Downhill		0.266	0.234	0.215	0.220	0.193	0.173	0.262	0.221	0.193
	Uphill		0.320	0.285	0.265	0.238	0.211	0.191	0.281	0.239	0.211

- The inter-story drift ratio decreases with an increase in the characteristic strength of isolation system for a given base-isolated building.
- The drift ratio is observed to be more in the portion of the building below the uppermost foundation level when wind is blowing in the uphill direction.

Conclusion

- Following conclusions are drawn from the present study:
  i. Lead-rubber bearing is effective to reduce the seismic demand in the buildings with split foundation; however, the effectiveness is less in 2-story building model.

  ii. The displacement of isolator at uppermost foundation level is found to be more than that of the isolator at the lowermost foundation level under earthquake loading. Therefore, appropriate selection of isolation parameters is extremely important to minimize the differential displacement between different isolator levels in the split foundation building.

  iii. The explosion near the lowermost foundation level is more damaging as compared to the same at uppermost foundation level in case of buildings on split foundation.

  iv. The careful selection of isolator parameters is required when other hazards are significant along with the earthquake load.

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