EFFECT OF FLOATING COLUMNS ON THE SEIMIC RESPONSE OF INFILLED RC BUILDINGS ON HILLS

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ABSTRACT

Buildings constructed on sloping terrain are highly vulnerable to damage in the event of an earthquake as a result of the presence of mass and stiffness irregularities that arises from the structural configuration. The devastating consequences of such constructions have been observed in the aftermath of past earthquake events such as the 2011 Sikkim Earthquake, 2013 Kashmir Earthquake and 2015 Nepal Earthquake to name a few. The high seismicity of the hilly and mountainous region of the Indian subcontinent further compounds upon the expected seismic risk in the region. Due to the unavailability of constructable lands in the region, common construction practices usually involve increasing the floor area of upper stories by introducing horizontal projections beyond the boundaries of the underlying stories resulting in columns resting on beams more commonly known as "floating columns". Such structural elements are highly undesirable due to the discontinuity in the vertical load path and are prohibited as per the recommendations of IS 1893 (2016). The present study aims at shedding light on the effect of presence of floating columns on the seismic response of Un-Reinforced Masonry (URM) infilled RC buildings on sloping terrain. An analytical study is performed on a set of URM infilled RC buildings with structural configurations commonly found on sloping terrain. Seismic response and collapse mechanism are compared for buildings with and without floating columns by performing non-linear time-history analyses. The variation of Peak Spectral Acceleration (PSA) along the height of the building was very close for the respective buildings but was higher for buildings with floating columns as compared to their regular counterparts. It can be observed that Inter-storey Drift Ratio (IDR) was significantly higher for buildings with floating columns. The damage was overall higher with the introduction of floating columns in the vertical configuration of the building. Concentration of stress was observed in floating columns when it was intoduced in the intermediate frame along the slope of the terrain.

Keywords: *Floating columns, hill building, non-linear time-history analysis, RC building, URM infill*

1. INTRODUCTION

India subcontinent is one of the most seismically active regions in the world having experienced a number of devastating events in the past such as the 2002 Bhuj earthquake, 2011 Sikkim Earthquake, 2015 Nepal Earthquake, 2020 Assam earthquake, etc. to name a few. Such events had a huge economic and social toll on the affected region (Sharma et al. 2013; Rai et al. 2016). Proper codal provisions and guidelines for earthquake resistant design have been developed for the Indian scenario to ensure the safety of the people and the built environment in the event of an earthquake. However, specific provisions are not available for buildings constructed on sloping terrain in the hills and mountainous region of India. Due to the nature of the terrain, buildings constructed on sloping terrain are extremely vulnerable to damage in the event of an earthquake as a result of their intrinsic horizontal and vertical irregularities. In addition, due to the lack of proper constructible lands, buildings are often constructed with floating columns to accommodate for larger floor area of upper stories creating overhangs (Fig. 1). Another similar scenario occurs when due to the constraint of space, storage areas or parking spaces are accommodated by providing large open spaces with the removal of a few columns. All the types of construction practices lead to the presence of columns which lack direct vertical load transfer path to the foundation more commonly known as floating columns.

(a) (b)

Fig. 1. Hill buildings with floating columns

These design practices have shown to be detrimental to the seismic performance in the past earthquakes as a consequence of concentration of stresses on specific vertical load resisting elements. IS 1893 (2016) prohibits the presence of floating columns along the height of the building. Using non-linear dynamic analyses an attempt has been made in the present paper to understand the effect of floating columns on the overall seismic performance of buildings on sloping terrain.

2. METHODOLOGY

To perform the comparative study, a generic plan is considered with plan dimensions 25.6*m* x 15*m* as shown in Fig. 2(a). Two different structural configurations are considered that are common in the hilly cities of India viz., split foundation (Fig. 2(b)) and step-back buildings (Fig. 2(c)), hereafter identified with prefixes 'SF' and SB respectively. For the purpose of simplicity, the portion of the building above the uppermost foundation level is hereafter referred to as the 'superstructure' while the portion lying below it is referred to as the 'basement'. The first set of Un-Reinforced Masonry (URM) infilled RC hill buildings with floating columns are modelled with discontinuity in the vertical load resisting system in the interior frames considered along the slope of the terrain and are hereafter identified with suffix 'FC'. Floating columns are introduced at the storey above the plinth of the superstructure since these commonly used as parking area (Fig.2 (d) and (e)). The second set of buildings are modelled with horizontal projections which result in misalignment of vertical load resisting elements at the ground storey of the superstructure (Fig.2 (f) and (g)), hereafter identified with suffix 'OH'. These structural configurations are generally prevalent where due to the lack of appropriate constructible lands, a higher floor area is provided at the upper stories. To reflect the 'OH' construction practices, the number of bays along the direction of slope has been decreased at the plinth level of the superstructure (Fig.2 (f) and (g)). The length of the overhang generally varies from building to building between 1.0*m* to 1.5*m* and considered as 1.2*m* for the present study.

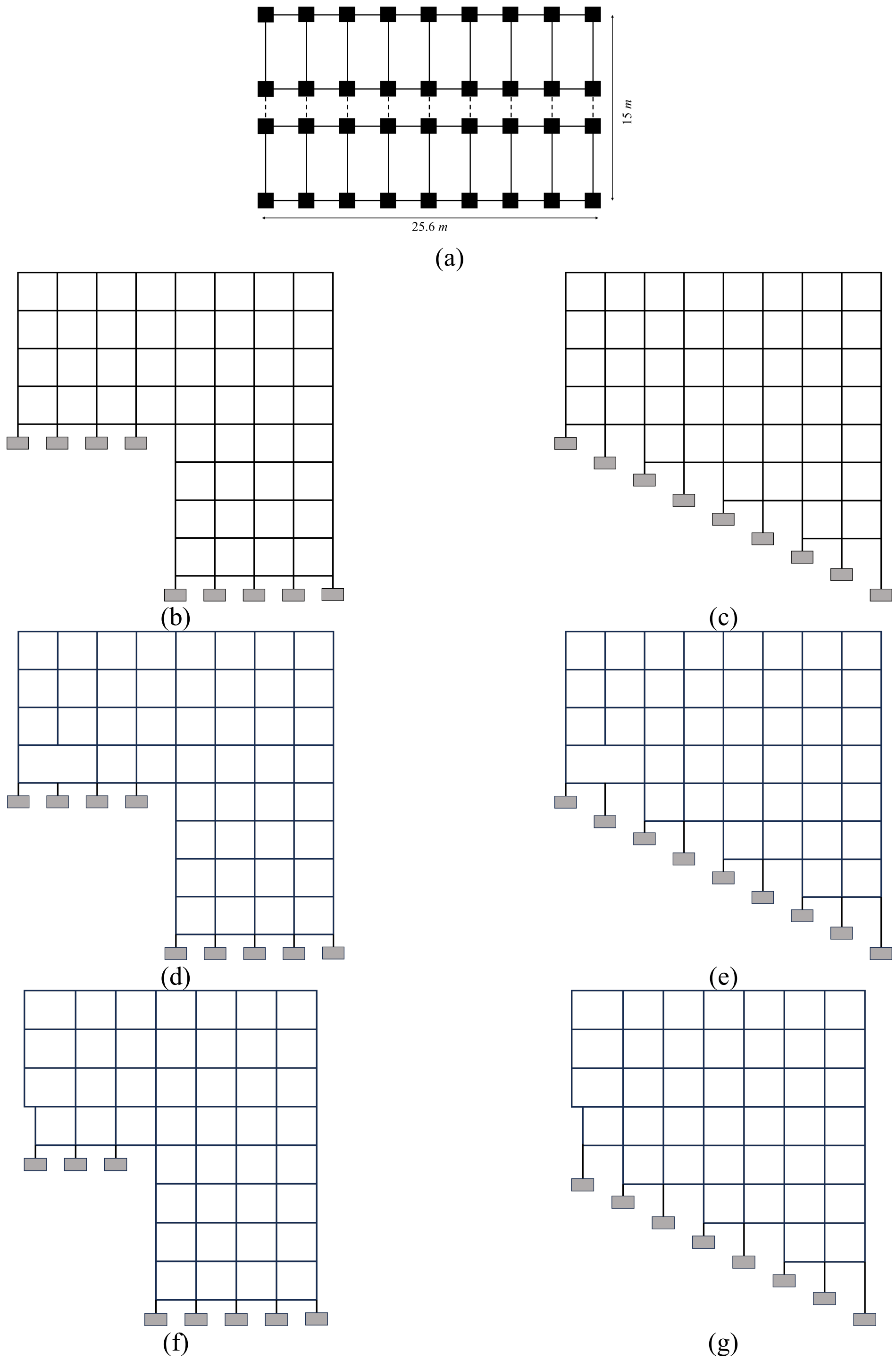
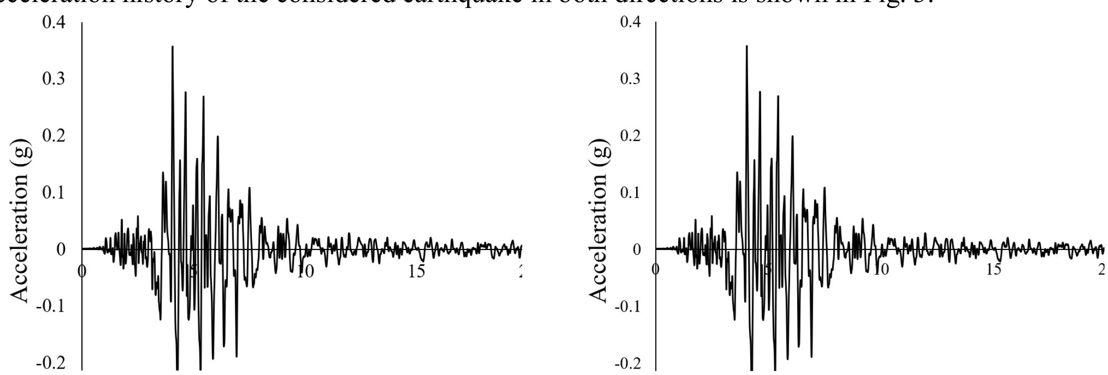


Fig. 2. (a) Plan; and elevation of building with (b) split-foundation (SF); (c) step-back (SB) (d) split-foundation and intermediate floating columns (SF-FC); (e) split-foundation and overhanging floating columns (SF-OH); (f) step-back and intermediate floating columns (SB-FC); and (g) step-back and overhanging floating columns (SB-OH)

All buildings are designed as Special Moment Resisting Frames (SMRF) considering provisions of IS456 (2000), IS1893 (2016) and IS13920 (2016). Dead Loads and Imposed Loads (for residential buildings) are considered as per IS875 (1987a) and IS875 (1987b) respectively. All the considered buildings are situated in seismic zone IV on soil type I IS1893 (2016). All structural members have been proportioned to ensure that the maximum percentage of reinforcements lie between 1-1.5% on each face of beam and 0.8% - 4% of the gross section area of the columns. The resulting section sizes are 300*mm* x 400 *mm* and 350*mm* x 350*mm* for the beam and columns respectively. The section size of the overhang beams is taken as 400*mm* x 500*mm* and the underlying columns as 400*mm* x 400*mm* to accommodate the additional design loads and moments acting on them. However, a higher cross section of 650*mm* x 650*mm* was required for columns with 1.1*m* and 2.75*m* heights in the step-back buildings. Rigid diaphragms action of reinforced concrete slab has been considered in the analytical model. The complex interaction of the frame and infill elements play a crucial role in the overall seismic response of the building. A number of modelling techniques are available for modelling the infill panels (Mallick and Severn 1967; Rodrigues et al. 2010; Asteris et al. 2011; Haldar et al. 2012). In the present study, infill panels are modelled as eccentric diagonal struts as per Haldar et al. (2013) having width as per IS1893 (2016). Fair grade masonry with compressive strength 4.14*MPa* is considered as per Haldar et al. (2012). To simulate the non-linear response, lumped plasticity approach has been adopted with the help of moment (M3) hinges as per ASCE-41 (2017) at each end of the beam and fiber P-M2-M3 hinges at each end of the column. In addition, shear hinges are provided at each end and at the middle of the column elements with shear capacity calculated as per ASCE-41 (2017). The shear damage and failure of the infill struts are simulated with the help of shear hinges modelled as per ASCE-41 (2013) and Haldar et al. (2013a); Haldar (2013b).

3. NON-LINEAR DYNAMIC ANALYSIS

Seismic assessment of buildings can be achieved by a number of methods. Non-linear static methods are in good agreement with the realistic behaviour of building with regular configuration. However, owing to horizontal and vertical irregularities, the considered buildings are expected to show extreme inelastic behaviour and are sensitive to cyclic strength degradation. Therefore, dynamic non-linear time-history analysis is adopted for determining the seismic response of the considered buildings. For this purpose, the 1976 Friuli earthquake has been considered due to its high magnitude (6.5*Mw*) and its PGA (0.35*g*) closely resembling the expected earthquake intensity of hilly regions. The ground acceleration history of the considered earthquake in both directions is shown in Fig. 3.



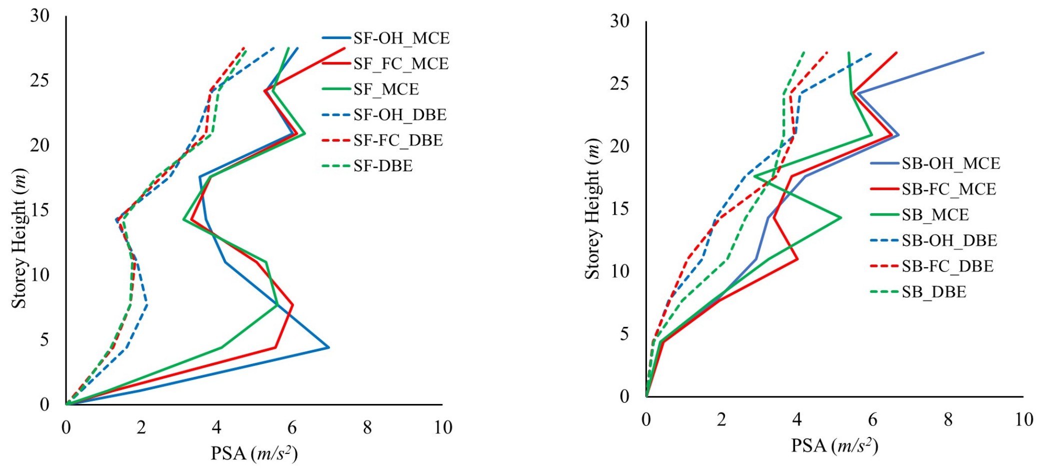
(a) longitudinal direction (b) transverse direction

Fig. 3. Ground motion record of 1976 Friuli Earthquake

Considering high nonlinearity of the irregular building configurations, the ground motion has been applied bidirectionally in order to estimate the response of the buildings. The ground motions are scaled to match the target spectral acceleration at the fundamental period of vibration (T1) of the building corresponding to Design Basis Earthquake (DBE) and Maximum Considered Earthquake (MCE) for Zone IV as per IS1893 (2016).

3.1 Peak Storey Acceleration

The Peak Storey Acceleration (PSA) is the maximum acceleration sustained by any joint of a particular storey as a result of the input seismic excitation. It is an indicator of the inertial forces developed in the individual stories over the duration of the ground motion. The variation of the PSA, taken as the maximum in both directions along the height of the building both for DBE and MCE hazard level as shown in Fig. 4.



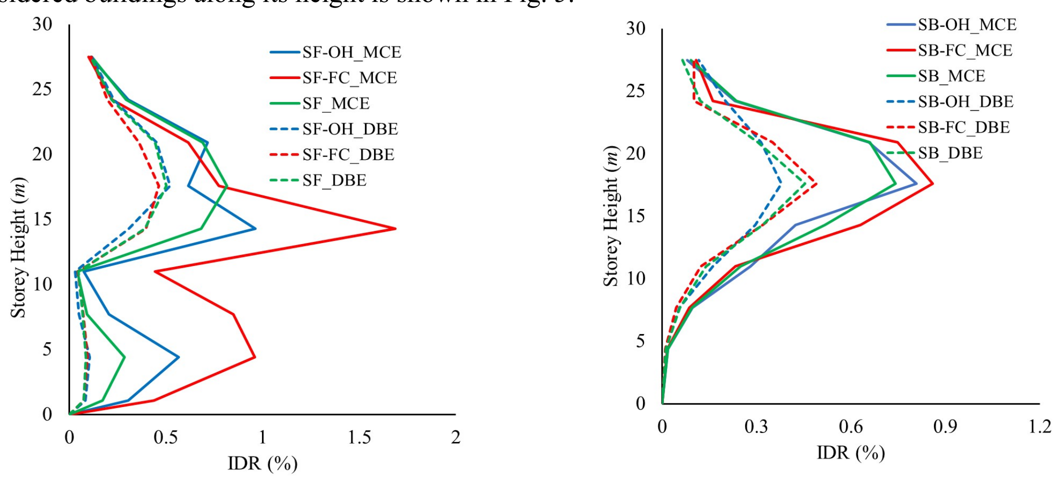
(a) (b)

Fig. 4 Variation of PSA along the height for (a) split-foundation and (b) step-back buildings

The PSA along the height of the building is quite similar for all the considered buildings especially at DBE hazard intensity. At MCE hazard intensity, the PSA is slightly higher for buildings with overhangs which is followed by building with intermediate floating column and is least for buildings without any floating column.

3.2 Inter-storey Drift Ratio

The Inter-storey Drift Ratio (IDR) is a seismic response parameter that is indicative of the damage expected at different storeys of the building. IDR is calculated as the ratio of the relative lateral displacement at floor level in a storey to the height of the storey. The variation of IDR of the considered buildings along its height is shown in Fig. 5.



(a) (b)

Fig. 5. Variation of IDR along the height for (a) split-foundation and (b) step-back buildings

It can be observed from Fig. 5 that IDR is higher for buildings with floating columns ('OH' and 'FC') as compared to ones without floating columns ('SF' and 'SB'). Floating columns in interior frame ('FC') shows the highest IDR both for step-back ('SB') and split-foundation ('SF') buildings followed by buildings with overhang ('OH'). In the case of building with split-foundation (SF-FC building), the maximum IDR increases by 108.6% due to the presence of floating columns while the increase was significantly lower (16%) for step-back buildings (SB-FC building).

3.3 Damage Pattern

The damage pattern observed for Split-Foundation buildings at MCE hazard level (0.24*g*) are shown in Fig. 6. It can be observed that the extent of damage is highest in the short columns just below the plinth level of the superstructure. These short columns experience a combination of shear failure and flexural yielding while the remaining short columns remain relatively undamaged. Flexural damage of beams is observed in a majority of the beams especially in the superstructure. In addition, the presence of floating columns causes concentration of stresses resulting in shear damage of the floating column in building SF-FC while such damage was not observed in its other two buildings (SF and SF-OH).

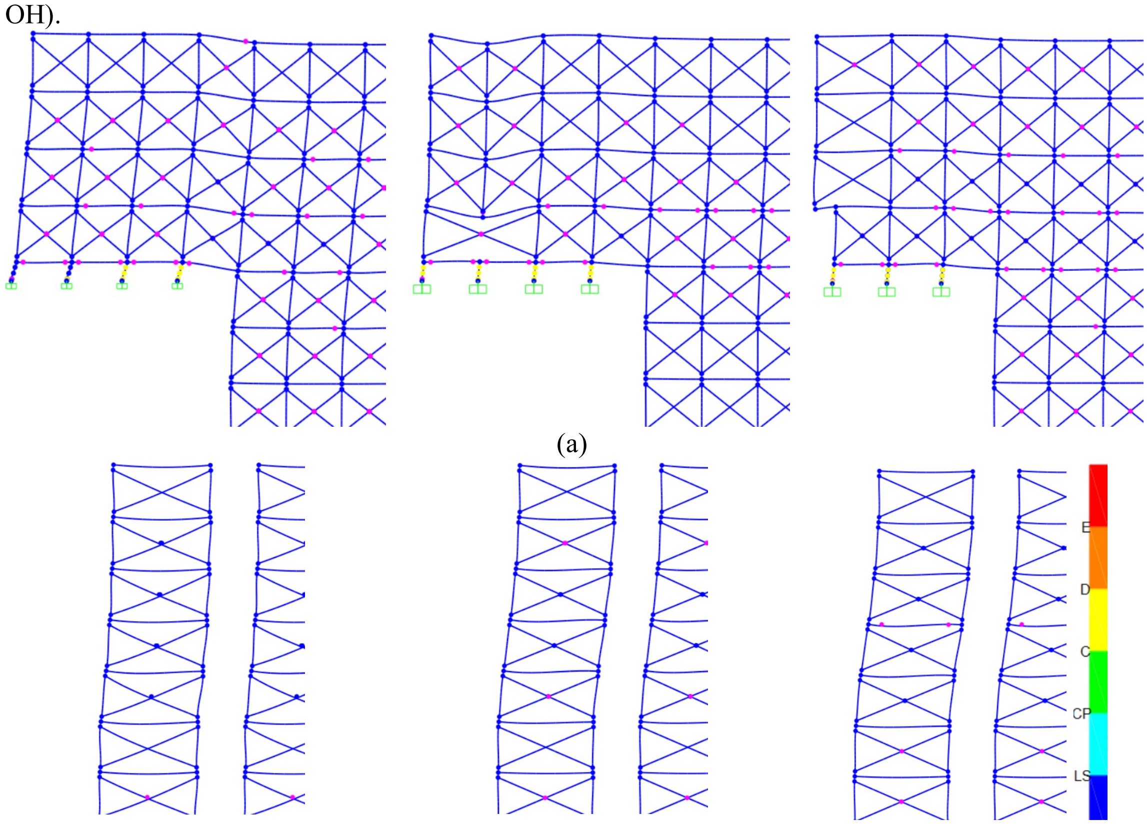
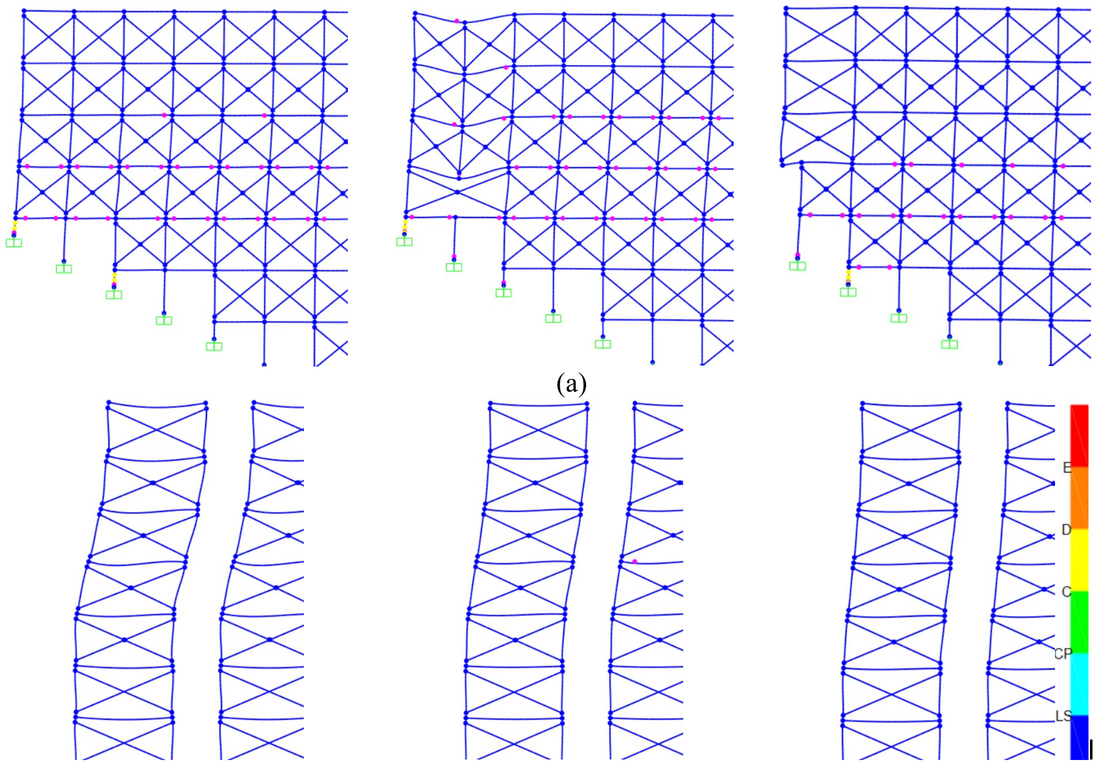


Fig. 6. Damage pattern in split-foundation buildings (a) along; and (b) across the slope of the terrain

Damage is observed in a majority of the infills in all buildings considering both directions but the extent of damage in infills is more pronounced in the direction across the slope of the terrain. The extent of damage in infills is observed to be highest in building SB-OH where a majority of the infills at the top storey are damaged.



(a)

(b)

Fig. 7. Damage pattern in step-back buildings (a) along; and (b) across the slope of the terrain

In the case of step-back buildings, the structural elements most vulnerable to damage are the short columns just below the plinth level of the superstructure and the top storey of the basement (Fig. 7). In case of buildings SB-OH and SB-FC, the short columns of height 2.75*m* also experience flexural yielding. In addition, beams of the first two storeys of the superstructure are damaged in the direction across the slope of the terrain. Damage due to concentration of stress is observed in building SB-FC in the floating column as well as the beams lying above the floating column even at the top storey.

4. CONCLUSIONS

The seismic response of buildings with floating columns in its vertical configuration has been determined and compared with their counterparts without floating columns. The presence of floating columns causes only minor variation in the peak storey acceleration along the height of the building especially at the DBE hazard level. However, at the MCE hazard level, the PSA was overall slightly higher for both 'OH' and 'FC' buildings as compared to their regular counterparts. A larger variation was observed in the inter-storey drift ratio. The maximum IDR of SF-FC was found to be 108.6% higher than SF while a lower variation (16%) was observed for step-back buildings indicating a higher increase in seismic vulnerability of split-foundation buildings in the presence of floating columns. The maximum IDR of buildings with overhanging floating columns ('OH') was found to be higher than the regular buildings but lower as compared to buildings with floating columns in the intermediate frames ('FC'). Damage pattern observed in the respective buildings indicate that the most vulnerable structural elements are similar for all buildings which are the short columns in the upper stories of the basement or just below the superstructure. However, concentration of stress in the floating column was observed for buildings 'FC' increasing the overall vulnerability of such construction practices. The overall observed damage was also found to be higher for buildings with floating columns as compared to their regular counterparts.

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