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Common irregularities and its effects on reinforced concrete building response

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Abstract. In most of the countries, the irregular building construction is popular for fulfilling both aesthetic and functional requirements. However, the evidence of past earthquakes in Nepal and the globe demonstrated the higher level of seismic vulnerability of the buildings due to irregularities. Considering this fact, the present study highlighted the common irregularities and its effect on reinforced concrete building response. The effect of structural irregularities was studied through numerical analysis. The geometrical, mass and stiffness irregularities were created by removing bays in different floor levels and removing the columns at different sections respectively. In this study, the numerical models were created in finite element program SAP2000. The structural performance was studied using both non-linear static pushover and dynamic time history analysis. The results indicate that the level of irregularities significantly influenced the behavior of structures.

Keywords: RC buildings, pushover analysis, structural irregularities, time history analysis

Распространенные дефекты и их влияние на характеристики железобетонного здания

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Аннотация. Во многих странах погрешности в проектировании зданий часто сказываются не только на их эстетическом виде, но и на техническом состоянии. Череда землетрясений, произошедших как в Непале, так и во всем мире, продемонстрировала высокий уровень сейсмической уязвимости зданий из-за погрешностей их проектирования и возведения. Принимая во внимание этот факт, в настоящем исследовании освещаются общие дефекты и их влияние на характеристики железобетонных зданий. Влияние конструктивных погрешностей изучено с помощью численного анализа. Геометрические погрешности и погрешности в характеристиках

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материала конструкций и жесткостей их сечений моделировались путем удаления пролетов в различных уровнях пола и удаления колонн в различных местах соответственно. В процессе численного исследования были созданы конечно-элементные модели в системе SAP2000. Характеристики конструкции изучались с использованием нелинейного статического прогона и динамического расчета изменений во времени. Результаты показали, что количество дефектов существенно влияет на поведение конструкций.

Ключевые слова: железобетонные здания, сейсмический анализ, конструктивные дефекты, динамический расчет

Introduction

The behavior of structure during earthquake depends on the distribution of stiffness, mass, plan, strength and many other irregularities in both the vertical and horizontal direction of the structure [1]. The past scenarios of damages of the buildings indicated that the irregularity was major reason behind the failure of the structures during strong ground shaking [2]. When the structure is subjected to earthquake, the horizontal forces is generated in the structure and this produced inertia forces acting through the center of mass of the structure. All these forces are resisted by the vertical columns and walls; and resultant of these forces act through a point known as center of stiffness. The level of horizontal and vertical irregularities is very sensitive for structural performance during strong ground shaking.

To perform well against seismic forces, structure should be subjected to adequate lateral strength, simple and regular configuration, sufficient stiffness and ductility. Buildings with simple geometry and uniformly distributed mass and stiffness in plan and elevation are less vulnerable in comparison to the structures with irregular configuration [3]. Many building structures are irregular in some sense. Some have been initially so designed and others have become so by accidently. For example, structures can irregular due to inconsistence or even errors during the construction process while many have been rendered irregular during their life time because of damage, rehabilitation or change of use. Vertical irregularities in buildings are imposed by city regulations and structural designers have to earthquake response. Furthermore, the main vertical irregularities examined by the researchers are: stiffness irregularity, mass irregularity, vertical geometric irregularity, in-plane discontinuity, discontinuity in capacity. Similarly, the horizontal irregularities are basically due to asymmetrical plan shapes, re-entrants' corners, diaphragm discontinuity and torsional irregularities [4].

In the modern era, irregular structures are quite frequently being built in almost every country including Nepal. Irregular structure is being popular in multi-storied building because of its both aesthetic architecture as well as its functional use. Besides, this land limitation is the main cause for providing adequate daylight and ventilation for the lower story in the urban area with closely spaced tall buildings. From the view point of seismic safety, fundamental period, base shear and most importantly stress concentration and ductility demand in localized in the structure. Thus, during an earthquake, geometrical regular shape structure with uniform mass and stiffness has good performance as compared to vertically irregular structures. To this end, the geometrical, mass and stiffness irregularities were created by removing the bay in different floor levels and removing the columns at different sections respectively.

Classification of irregularities

Many researchers have focused on the vertically irregular structures leaving behind the influence of configuration and plan irregularity. However, the past earthquakes in Nepal and globe clearly indicated the risk level in different irregularities. It can also be seen that the major challenges in the seismic design of every structures because of excessive torsional responses and stress concentration at every corners of the buildings. The best example of the stress concentration is the re-entrant corner in the *L*-shaped, *T*-shaped and *U*-shaped buildings that causes heavy stress concentration due to changes in stiffness and torsional amplification. The stress concentration is the main reason for early failure of the structure [5]. The main irregularities in structures can be summarized as follows.

Mass irregularities. If there is the variation of more than 150% of mass between the adjacent story then it is considered as mass irregularity (see Figure 1). During the time of earthquake, high rise as well as small structures are generally subjected to failure due to the presence of several irregularities such as strength, mass, discontinuity in capacity and restrained corner [6]. Several building structures are damaged during Bhuj, Chili and Gorkha earthquake are due to the mass irregularities. The higher amount of mass leads in the reduction of ductility of vertical load resisting elements and leads to the collapse of structures. The heavy mass on upper story leads the structure to the vulnerable condition than those at lower story level [7]. From the analytical study of different regular and irregular buildings, it is noticed that the type, magnitude and location of irregularities had strong influence on collapse capacity of the structures. The buildings having stiffness, setback and strength irregularity at the bottom storey has less collapse capacity [8]. The trend of variation of collapse capacity was observed to be reverse for regular buildings. For mass irregular buildings, the maximum impact on collapse response was observed for the case when mass irregularity was present at the top story [9]. The plan irregular building models showed less sensitivity to collapse response as compared to the vertical irregularities. This may be due to least sensitivity of seismic response to plan irregularity.

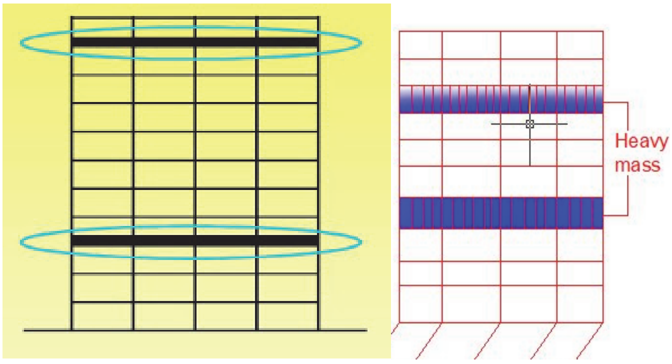


Figure 1. Representation of mass irregular structure

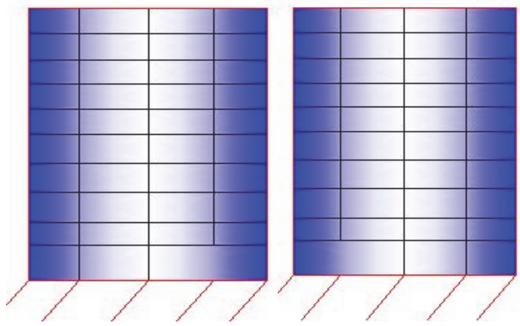


Figure 2. Representation of stiffness irregularity of the structure

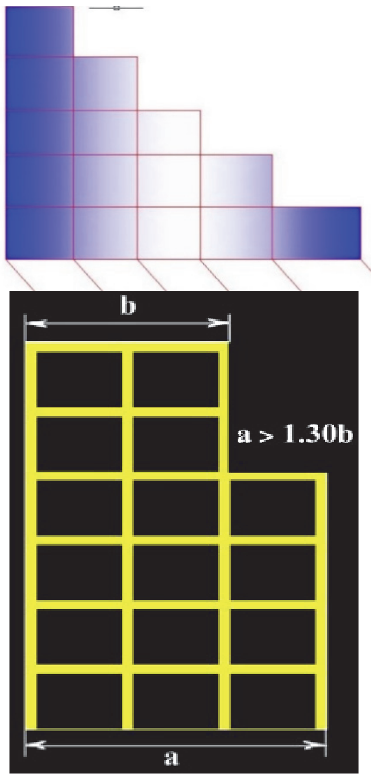


Figure 3. Representation of geometrical irregularity of the structure

a *b*

Figure 4. Representation of geometrical irregularity of the structures:
a – top storey high weight; *b* – top storey fully infilled while lower storey is in bare frame

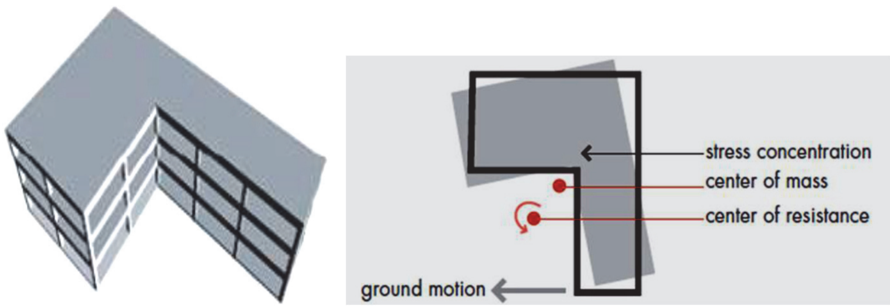


Figure 5. Condition of stress concentration in the structure

Stiffness irregularities. If the lateral stiffness is less than 70% of that in the storey above or less than 80% of the average stiffness up to 3 storey then it is said to be soft story [10]. During the earthquake in Chili, several number of buildings around the alto-Rio building were badly damaged but safe while the alto-Rio building got completely collapsed due to vertical irregularities in the stiffness [11]. The performance of the structure also depends on the lateral shear stiffness or flexural stiffness. The lateral shear stiffness of the story can be found by using following relation. The representation of stiffness irregularity is shown in Figure 2.

$$Ki = \sum_{j=1}^{nc} \frac{12EjIj}{Lj^3} + \sum_{m=1}^{n_{\text{strut}}} \frac{AmEm}{Lm} \cos^2 \theta m,$$

where nc – total number of continuum columns in the i-th story; n_{strut} – the total number of struts in i-th story; Ej – modulus of elasticity of materials; Ij – moment of inertia of the member; Lj – length of column; Em – elastic modulus; Am – axial area; Lm – length; θm – angle of inclination with respect to the horizontal axis of strut.

Geometrical irregularities. If the horizontal dimension of the lateral force-resisting system in any story varies by more than 130% of adjacent story in both the above and below level, then it is said to be vertical geometric irregularities [12]. This type of irregularity exists in elevation (Figure 3).

Horizontal irregularities. These types of irregularity exist if any element of the lateral load resisting system is not parallel to one of the orthogonal axes of the lateral load resisting system of the entire structure (Figures 4 and 5). Among different horizontal irregularities, torsional irregularity is one and can be removed by increasing column sizes by bracing and adding the shear wall [13].

Description of study buildings and modelling procedure

Description of the buildings. In this study, one regular and four irregulars RC moment resisting frame structure are taken for analysis. The detailed information of the studied building structures has been collected from the drawing by consultants, municipality drawing and a field survey of existing buildings in Pokhara Metropolitan City. The collected information helps to know the reason behind the construction of irregular structures, level of irregularity and the status of irregular building structures in the locality. The typical building model used in the study is the real model. For further analysis, the building models are modified to address the different irregularity types.

To extract more detailed structural information such as the size and detailing of RC elements (beam and column), inter-storey height by width, type of steel reinforcement and quality of concrete are the same to all study models. To study the influence of irregularity in performance of structures, all the building models are prepared and analyzed with a three-dimensional model. The material properties of the building are assumed to be same in all the buildings and throughout the height. Here, building models used in the analytical study are considered to have 7 bays 4 m width in *X*-direction and 3 bays of 4 m width in *Y*-direction with 3 m storey height. The bay width is kept 4 m on the basis of standard code in the region. The plan of the building model is presented in Figure 6.

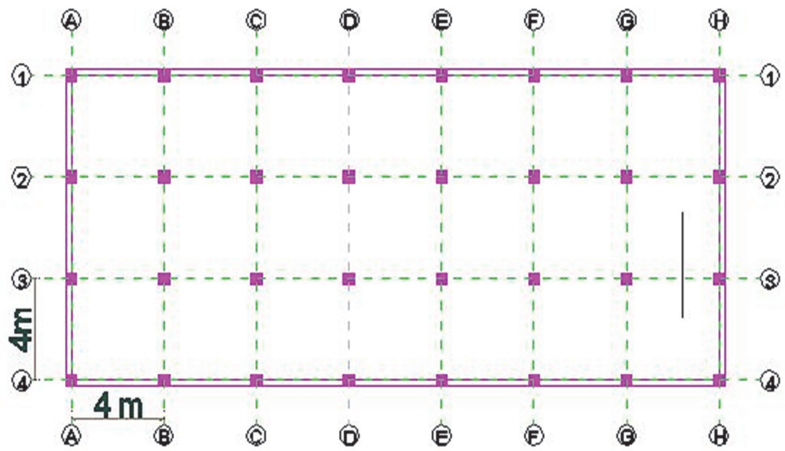


Figure 6. Plan of study building model

For numerical analysis, non-linear static pushover and non-linear dynamic time history analysis are used. The regular building is kept regular throughout the seven story whereas some bays are removed in different story in case of irregular buildings. In IRR1 type irregular building one bays in *X*-direction is removed in each story of the buildings. In IRR2 type irregular building two bays in *X*-direction is removed from each two story of the building respectively. In IRR3 building 3 bays in *X*-direction are removed from G+ three story of the buildings while in IRR4 type irregular buildings 4 bays in *X*-direction are removed from G+ four story of the buildings. The parameters used for design of regular and irregular building models is presented in Table 1.

Table 1

Parameters used for design of regular and irregular buildings models

Parameters	Details	Unit
No of storey	7	
Floor height	3	m
Thickness of infill wall	230	mm
Imposed load on roof	1	kN/m^2
Imposed load on regular floor	3	kN/m^2
Floor finish load	1	kN/m^2
Wall load	4.4	kN/m^2
Size of column	450×450	mm×mm
Size of beam	350×350	mm×mm
Slab thickness	150	mm
Grade of concrete, f_{ck}	20	MPa
Grade of steel	415	MPa
Specific weight of concrete	25	kN/m^3
Soil type	Medium	
Seismic zone	V	
Zone factor	0.36	
Importance factor, I	1	
Response reduction factor, R	5	
Poisons ratio	0.2	
Modulus of elasticity (infill), E_m	5310	MPa
Modulus of elasticity (concrete), E_c*	25 000	MPa
Time history data	El Centro	
Damping ratio	5	%
Thickness of shear wall	250	mm
Angle of friction of soil	30	Degree
Specific weight of soil	18	kN/m^3

Note: * $E_c = 5000\sqrt{fck}$.

Numerical analysis method. The most accurate procedure for structure subjected to strong ground motion is the time-history analysis. The pushover analysis is less onerous than nonlinear dynamic analysis since it does not require the monitoring of cyclic inelastic response of structural member and it avoids the dependence on the input motion [10]. The necessity for faster method that would ensure a reliable structural assessment or design of structure subjected to seismic loading led to the pushover analysis [14].

A pushover analysis is performed by the subjecting a structure to a monotonically increasing until structure become unstable or predefined displacement reached. Under incrementally increasing loads various structural elements may yield sequentially. Consequently, at each event, the structure experiences a loss of stiffness. Pushover analysis generate static pushover curve which plots an applied lateral load against displacement. The value of the lateral force incrementally increases with the transition of structure in the nonlinear zone, plastic hinge is formed. When analyzing frame structure, material nonlinearity is assigned to discrete hinge location where plastic rotation occurs according to the [15–16], or other set of code-based or user defined criteria.

Numerical analysis based on the bare frame building modelling with three dimensional models (see Figures 7 and 8). Modelling of the structure is carried out by using SAP2000. Nonlinear behavior occurs within the frame elements at the location of plastic hinge [17]. The plastic hinges are the points on a structure where one expects cracking or yielding. The automatic, user defined and generated hinges can be created in structural analysis program [18]. Automatic hinge properties cannot be modified. User defined hinge properties can be viewed and modified based on the member cross section and reinforcement detailing. Only automatic and user defined hinge properties are assigned to a frame element. And once the automatic and user defined hinge are assigned program automatically create a generated hinge property for each hinge. Salihovic and Ademovic [19] interpreted the result by assigning auto hinge and user defined hinge with experimental data and concluded that auto hinge could not simulate the exact nonlinear behavior of the structure. Hence, in this study nonlinear static analysis is carried out by using default and user-defined plastic hinge properties.

On the beam section, the moment curvature relation established which gives ultimate moment, yield moment, ultimate curvature and yield curvature and the values were normalized with respect to yield moment and yield curvature, the plastic hinge length is taken as half of the depth of beam [16]. All the analysis is performed based on displacement-controlled procedure. The procedure for nonlinear analysis in this study is summarized as:

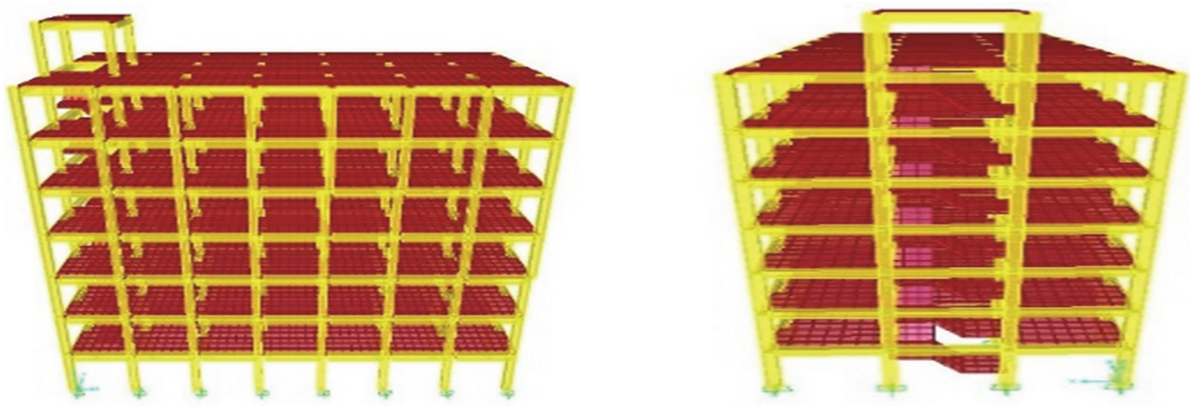
– application of 10% static lateral load induced due to earthquake at the CG of the building;

– developing (M–θ) relationship for critical region of beam and column;

– select control point to see the displacement;

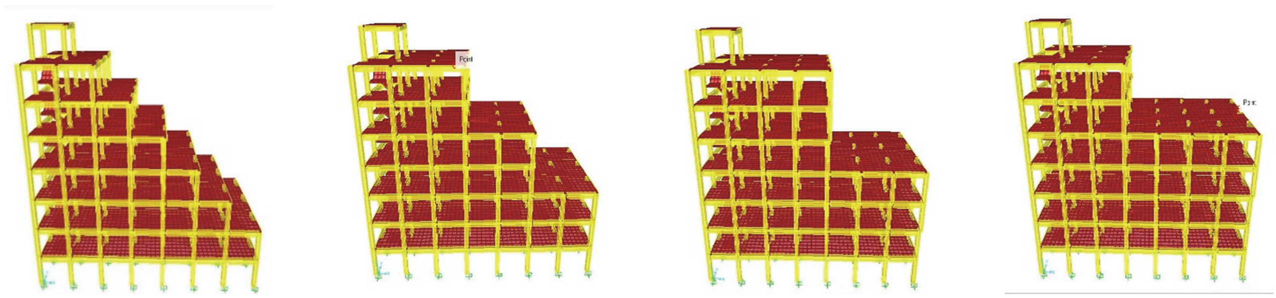
– apply full gravity load as a nonlinear static load pattern and gradually increasing lateral load, until the targeted displacement reached;

– developing hinge formation sequences and the base shear vs roof displacement (pushover curve) table.



a *b*

Figure 7. REG model with front elevation (*a*) and side elevation (*b*)



a *b* *c* *d*

Figure 8. Irregularities in the buildings:
a – IRR1 model (upto 2nd floor); *b* – IRR2 model (upto 3rd floor); *c* – IRR3 model (upto 4th floor); *d* – IRR4 model (upto 5th floor)

Analysis and interpretation of results

Pushover curves. From the pushover analysis, it is noticed that the regular buildings have immediate occupancy level before the performance point whereas irregular buildings reached life safety level before the performance point. In regular buildings, plastic hinges are evenly distributed from bottom to top storey level whereas in irregular buildings plastic hinges are formed in some of the beam only in the same storey level reaching the plastic limit earlier. The column of irregular buildings reached life safety and collapse prevention earlier than the regular buildings. From the pushover curve, it is clearly seen that irregular buildings have slightly higher base shear capacity.

From the hinge formation patterns, it is noticed that in regular building the life safety hinge are formed from bottom to top in regular status where as in IRR1 and IRR2 building the column of G+3 story get life safety hinge first. And at the time when G+3 story column gets life safety hinge the G+1 and G+2 story is in only immediate occupancy.

The results have shown that among the studied building types, regular buildings seem to have more capacity than any other steeped buildings. Regular buildings have higher stiffness compared to the buildings with floating columns. Irrespective of mass irregular building both of them have almost same capacity and have slightly less capacity than the regular buildings (see Figure 9).

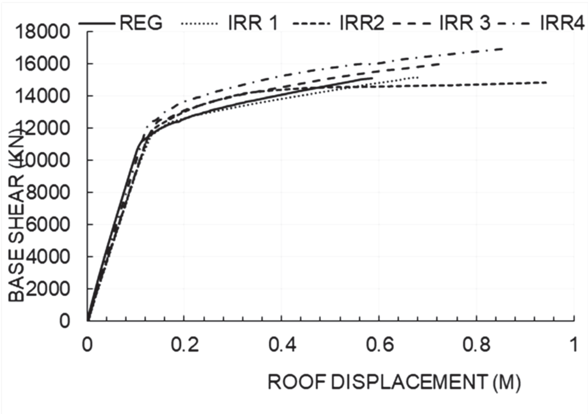
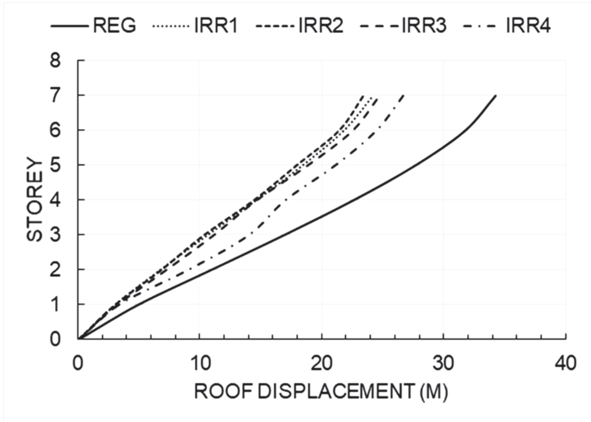


Figure 9. Comparison of base shear versus displacement of different regular and irregular buildings



a

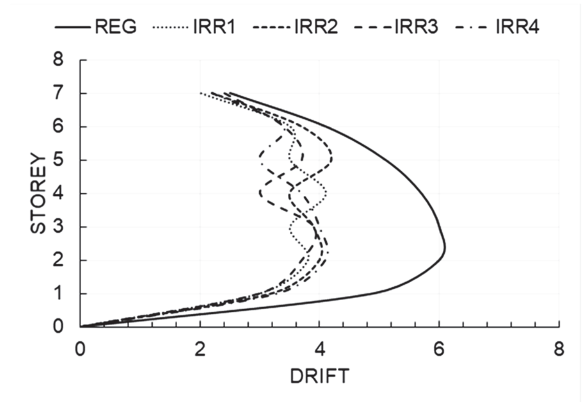
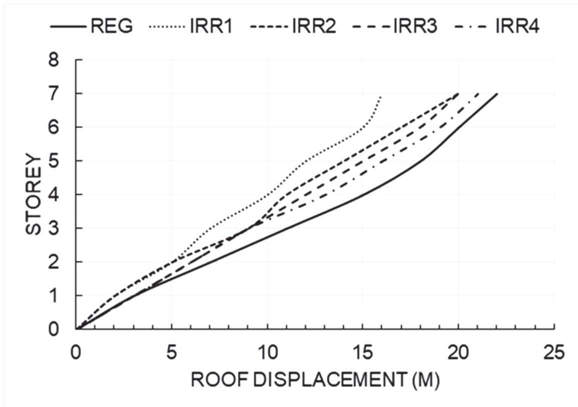


Figure 11. Story versus story drift in push *X*



b

Figure 10. Comparison of storey displacement, mm, of regular and geometric irregular buildings both in *X*- (*a*) and *Y*-direction (*b*) of loading

Displacements due to pushover analysis. From Figure 10, it is seen that the maximum displacement of the 7th storey regular building have more than that of the other irregular buildings. It is because there is more amount of mass upto top level in regular buildings compared to other irregular buildings. The same reason is behind the maximum top displacement in building model IRR3 and IRR4. These results justify that as the irregularity percentage increases in maximum displacement will decrease. However, due to torsional effects, the building model IRR1 has more displacement than IRR2 building model.

Comparison of story and story drift of structures. The story drift at the location of the steps building is changing abruptly as shown in figure in comparison to the regular buildings. The change in story drift is mainly noticed in the location of change of steps. The maximum story drift of irregular stepped buildings is seen less in comparison to the maximum story drift in regular building as indicated in Figure 11.

Time history analysis. The earthquake ground motion are important for dynamic analyses of the structures. Though, many earthquakes have been reported in the history of Nepal, no accelerations have been recorded. Due to the lack of actual time history data in Nepal, the dynamic time history analysis was performed with El Centro time history data (Figure 12). The analysis is good to represent the realistic behavior of structure [20].

From non-linear time history analysis as indicated in Figure 13, it is observed that the maximum top displacement of the regular building is 126.6 mm. The one step irregular buildings (IRR1) have displacement of 89.52 mm at the top while IRR2 have 94 mm and IRR3 have 95.98 mm at the top respectively. It is seen that maximum displacement of roof level in seventh story regular building than that of others irregular buildings. While comparing the result between the pushover and non-linear time history analysis the value of displacement of roof of the building given by non-linear time history is high compared to pushover analysis but the pattern of displacement of both the regular and geometric irregular building is same that is REG building had more displacement followed by IRR4, IRR3, and so on.

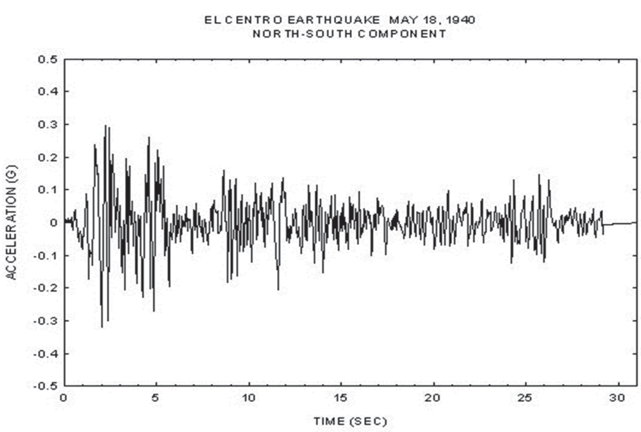


Figure 12. Earthquake time history data for El Centro earthquake

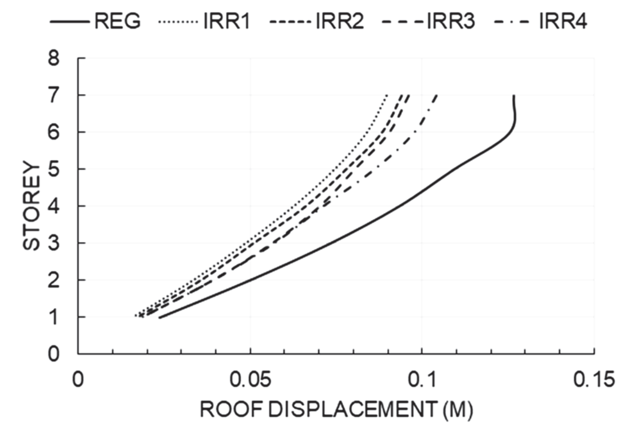


Figure 13. Story versus displacement curve from non-linear time history analysis

Comparison of moment of regular and geometric irregular buildings. The moment of regular and geometric irregular buildings is compared at the section of D–D. Here D11, D32, D42 likely D represents the value of moment at section D–D second place numerical value represents the place of moment taken as per plan of the buildings and third place numerical value represents story levels. Here the negative value represents that irregular buildings have more moment than regular buildings in percentages.

While comparing moment of regular and irregular buildings at section D–D, the moment of regular buildings is greater than IRR1 buildings upto the 2 story and slightly greater at 3 story level. But after the 3 storey level the moment of IRR1 buildings is greater than (52%) regular buildings. This is because the IRR1 building also have some configuration at bottom at two story but after bottom two story one bay is removed from each story creating geometrical irregularity. Hence, the moment is increased due to torsion in IRR 1 buildings through the mass is decreasing.

Similarly, to above result of IRR1 building, IRR2 building also have less moment than regular building (upto 13%) at lower story but at G+2 story level there is two bays removed creating geometrical irregularity. And after this story level moment of IRR2 building is greater than (upto 30%) regular building due to torsion induced in the IRR2 buildings through there is the reduction of the mass by the removal of the bay from upper story of buildings (Figures 14–17).

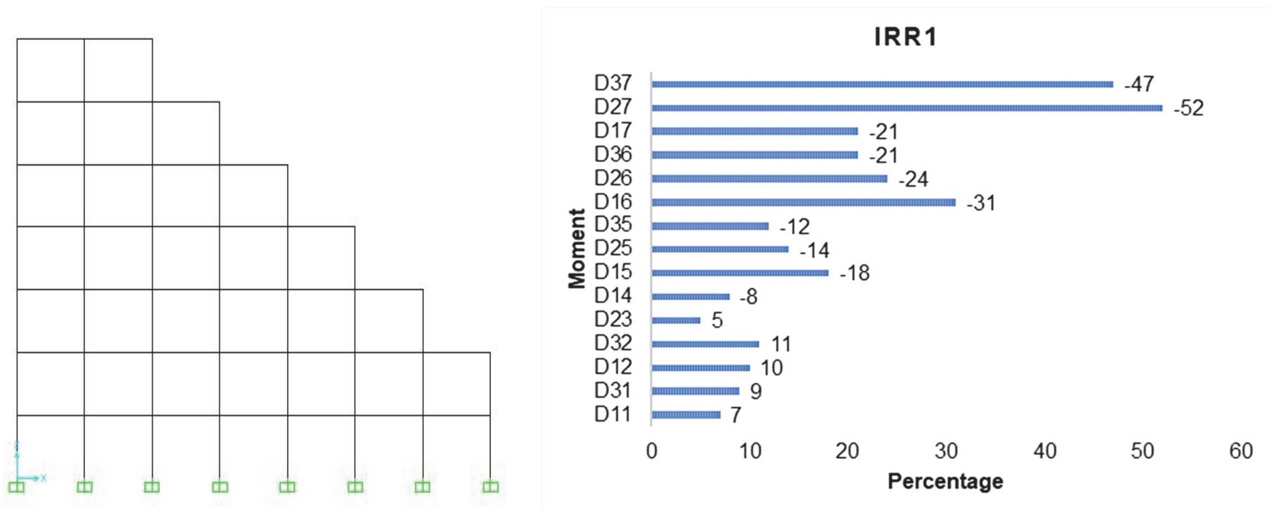


Figure 14. Plan and percentage increased or decreased of moment IRR1 with respect to regular buildings

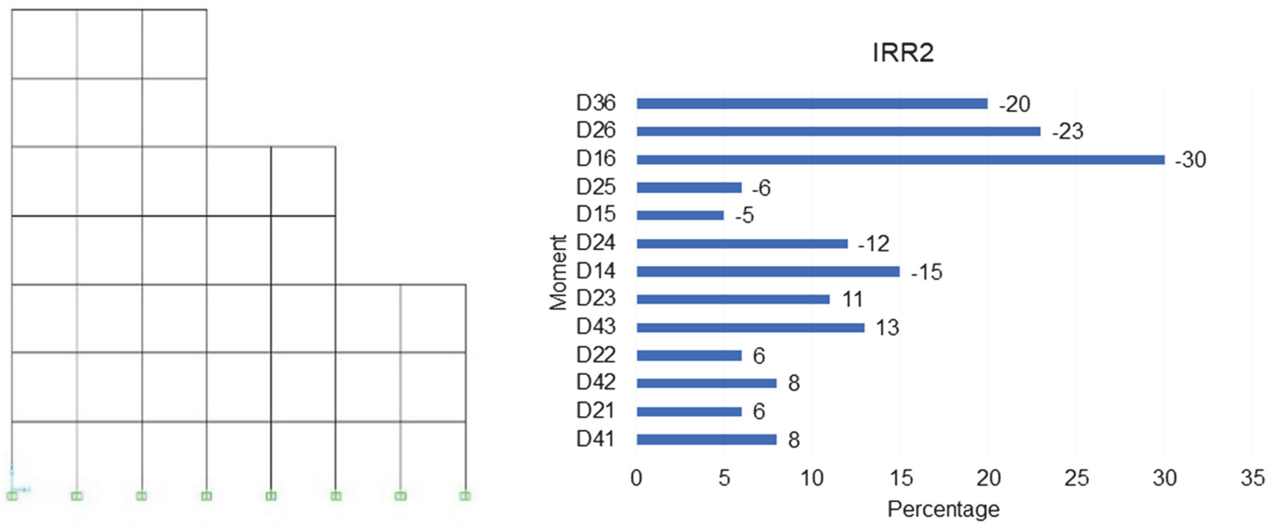


Figure 15. Plan and percentage increased or decreased of moment IRR2 with respect to regular buildings

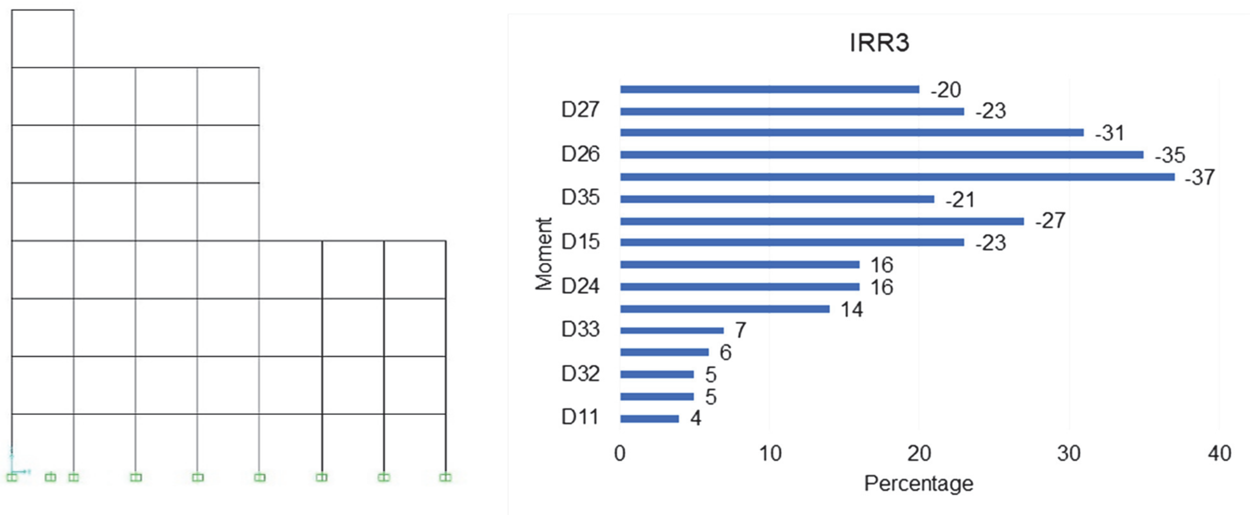


Figure 16. Plan and percentage increased or decreased of moment IRR3 with respect to regular buildings

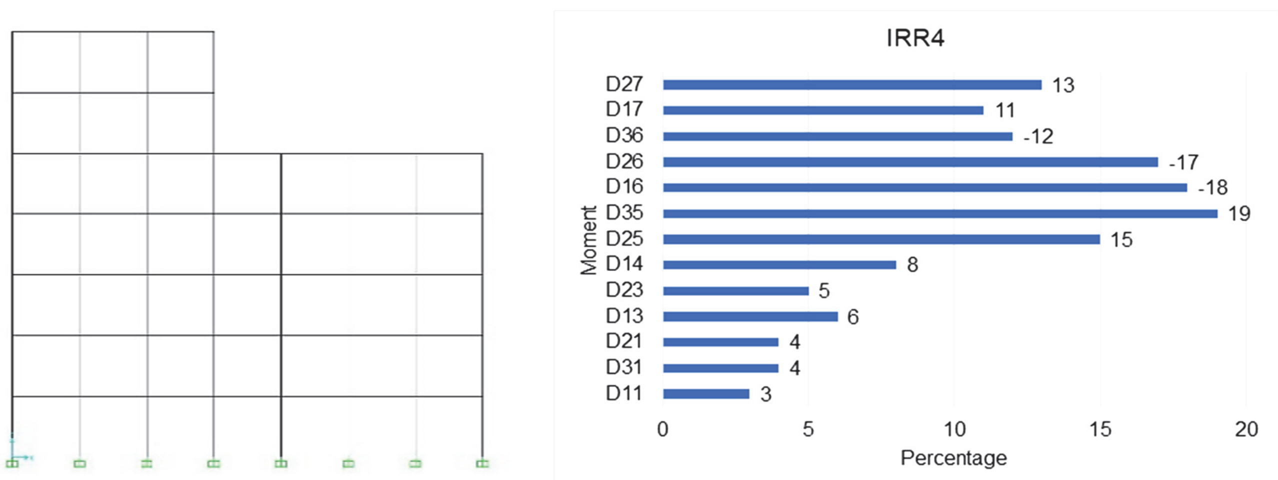


Figure 17. Plan and percentage increased or decreased of moment IRR4 with respect to regular buildings

Torsion effect on irregular building structures. Torsion is the twisting or wrenching of a structure by the exertion of forces tending to turn one end or part about a longitudinal axis while the other is held or turned in the opposite direction [21]. Torsion factor = Deflection U_{max} / (Deflection $U1_{max}$ + Deflection $U2_{max}$). The torsional factor of studied building models is presented in Table 2.

Table 2

Torsion factor of studied building structures

Storey	REG	IRR1	IRR2	IRR3	IRR4
7	0.559	0.669	0.519	0.575	0.531
6	0.558	0.564	0.524	0.572	0.526
5	0.557	0.683	0.714	0.565	0.776
4	0.554	0.765	0.732	0.748	0.785
3	0.552	0.826	0.820	0.756	0.790
2	0.552	0.871	0.826	0.757	0.794
1	0.553	0.874	0.829	0.758	0.796

From the Table 2, it is observed that regular building has almost same torsion factor from top to bottom whereas there is variation in other irregular buildings. It is noticed that there is 0.66 value at the seventh story and it increases to 0.87 at bottom story. Similarly, it follows same pattern in other three geometric irregular buildings.

Conclusions

This research explores the common structural irregularities and its effects on RC building response. To achieve the objectives irregularities were created by removing the bay in the building in different floors. The columns in the different section of the building structures were also removed for creating the irregularities in the study. The main outcomes of this study can be highlighted as:

– the non-linear time history analysis gives more roof displacement values of the same structures than the non-linear static pushover analysis;

– the column of irregular buildings reached life safety and collapse prevention earlier than the regular buildings. It reflects the good construction practices in beam column joints;

– the regular buildings have the higher roof displacement values as compared to the irregular ones. It is due to the effect of irregularity in the structures;

– the moment distribution of both regular and irregular building is more at bottom storey while in upper storey irregular buildings have more torsional effect and resulting higher moment than the regular one.

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