Seismic analysis of various combinations of irregularities in a structure

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Abstract. One of the important governing parameters of the seismic performance of a structure is its irregularities. There are many types of irregularities such as geometric irregularities, mass irregularities, irregularities due to varied column shapes and dimensions, etc. It is very evident that these irregularities are seen in every project in this contemporary world. We have to acknowledge that there is a tremendous scope for these irregularities to exist in combinations. Although there has been extensive literature on various irregularities and their combination, it was evident that authors restricted themselves to limited combinations. This paper investigates the seismic response of a multi-storeyed building induced with combinations of irregularities by varying the seismic parameters using STAAD Pro. Various configurations of mass and torsion irregularities in combination with other irregularities were induced in the structure and results of seismic response using response spectrum methods were assessed to arrive at novel solutions.

Keywords: Irregularities, Seismic analysis, Storey displacement, STAAD.Pro, Base shear

1. Introduction

In recent years, irregularities in a structure have become quite common to satisfy architectural and aesthetic purposes. The behaviour of any structure depends on the arrangement of its components and their placements. The vital aspect of any structural arrangement depends on geometry, shape, size of the structure which in turn affects the location of the centre of mass and centre of stiffness. When both the centre of mass and stiffness do not coincide, they tend to generate eccentricity. This eccentricity induces torsional coupling which results in damage of the structure. A number of papers have investigated the impact of varying shape, size and geometry of the structure under dynamic loading [4-6]. Irregular structures have variation or discontinuity in the plan, height, size, or combination of them which influence the behaviour of a structure when acted upon by horizontal forces. Some irregularities exist in the form of discontinuity in mass, stiffness and geometry along the elevation of a structure which can be categorized as vertical irregularities, whereas the horizontal irregularities are induced if there are discontinuities in the plan of a structure. The magnitude of variation of response of a structure to lateral loads depends on the types of irregularities, its location and intensity. In this modern society, it becomes quite important to choose the type of irregularities wisely during the design phase, especially for buildings in Zone 4 and Zone 5, to improve the performance of a structure and avoid any failure.

Till date, a lot of researchers have investigated the seismic response of a structure induced with vertical and horizontal irregularities [9-14]. Karavasilis and Bazeos [1] did a parametric study on an
inelastic seismic response of plain steel moment-resisting frame with vertical mass irregularity. The paper enlightens the role of inelastic deformation and the position of the mass in assessing the allocation of displacement along the height of a structure. Wang et al. [2] have designed a power plant with mass and vertical irregularity and assessed the structure's response by inducing the irregularities individually and in combination. The results depict the dominant effect of vertical irregularity over mass irregularity and increase in collapse risk due to the combined effect of irregularities. Georgoussis et al. [3] has investigated the accuracy and efficiency of the methodology based on Southwell’s formula and single-storey system model to assess the response of a building with mass and stiffness irregularities. Anvesh et al. [4] have studied the seismic analysis of a multi-storeyed building with mass irregularity and concluded that there is an increase of 67% in the moments of mass irregular buildings. Khan and Dhamge [5] highlighted the effect of mass irregularity on different floors of RCC buildings by response spectrum analysis using STAAD Pro and concluded that the decrease in shear force from the first storey to the top storey. Kostinakis and Asimina [6] investigated the influence of the in-plan irregularities induced by the random positioning of masonry in-fills on the seismic damage of the RCC building. The paper concluded that the highest inter-storey drift ratio caused by the in-plan irregularity can be 1.16 times more than the analogous value of the fully in-filled structure.

Doudounis et al. [7] studied the accuracy of the linear static model for the assessment of seismic response. Although the respective simplified static analysis seemed to be safely applied for the determination of the seismic response, in the case of tall buildings, the proposed distribution of seismic forces may have slightly underestimated the shears at the top storeys. Abd-el-Rahim and Farghaly [8] investigated the performance of gravity loaded irregular building in-plan under earthquake excitation. The top displacements for ‘T’ and ‘L’ shaped models are augmented up to 1.9-time top displacement in ‘I’-shaped model. Rahman and Salik [9] investigated the relative allocation of lateral forces progressed during seismic activity in every storey level of a structure owing to variation in the mass on vertically irregular structures. Naveen et al. [10] examined the seismic response of RCC structure possessed with various combinations of irregularities and concluded that the grouping of stiffness and vertical geometric irregularities has displayed highest storey displacement while the grouping of re-entrant corner and vertical geometric irregularities has depicted least storey displacement.

In the past literatures, researchers have extensively focused either on particular irregularities or have investigated the seismic response of the combination of two irregularities. The literature studies mainly depicted mass, stiffness and in-plan irregularities. In reality, there is scope for building to have multiple combinations of irregularities beyond two. According to the past literature study, the worst-case scenario of irregularities is stiffness irregularity in combination with vertical geometric irregularity. However, there is a lack in the literature on further combination of other irregularity in combination with stiffness and vertical irregularity. Hence, the present research investigates the seismic behaviour of structure induced with various combinations of irregularities along with Stiffness and vertical irregularity by response spectrum method using STAAD Pro. The various irregularities taken into consideration apart from stiffness and vertical irregularity include mass, re-entrant corner and torsion irregularity. A total of 52 cases have been investigated by varying the various input parameter and irregularity combinations, 9 cases with combination of 3 irregularities by varying soil types and 42 combinations of 4 irregularities by varying the configuration of irregularities. The primary objective of this investigation is to find the variation in the seismic response of a structure by comparing various irregularity combinations and find the critical cases.

2. Methodology

In this current project work, seismic analysis of a G+7 structure having 6 bays along both length and width with spacing of 3 m along both the directions are induced with various configurations of irregularities. Various cases were analysed by response spectrum method using STAAD Pro. Connect Edition. The major inputs which were taken into consideration were seismic zones, geometry of each
floor, soil type, elastic modulus and damping ratio. The earthquake zone, damping ratio and elastic modulus are taken as zone V, 0.5% and 21718400 kN/m² respectively as per IS 1893:2016 [15] which are treated as constant and each floor has been lumped with 4kN/m² load as per IS 875. Seismic responses of the structure induced with combinations of three irregularities were assessed by varying the soil types. Further, combinations considering four irregularities were assessed by keeping the base case as the combination of vertical and stiffness irregularity. The results of the seismic evaluation of the structure were in the outline of storey displacement and base shear. With the intention of validating the results, responses attained for the base configuration (the combination of vertical and stiffness irregularity) are compared with other combinations of irregularities.

2.1. Configuration of various irregularities
Irregularities in a structure are generated due to discontinuity in the structural parameters which exceed the standards. In this study, the base case is considered to be the combination of vertical and stiffness irregularity (VS), which are further integrated with other irregularities such as mass irregularity (M), re-entrained corner (R) and torsional irregularity (T) individually as shown in Table 1.

| Irregularity combination | Soil Type         | Nomenclature |
|--------------------------|-------------------|--------------|
| V+S+M                    | Hard (Type I)     | VSMH         |
| V+S+M                    | Medium (Type II)  | VSMM         |
| V+S+M                    | Soft (Type III)   | VSMS         |
| V+S                      | Hard (Type I)     | VSH          |
| V+S                      | Soft (Type III)   | VSS          |
| V+S+R                    | Hard (Type I)     | VSRH         |
| V+S+R                    | Medium (Type II)  | VSRM         |
| V+S+R                    | Soft (Type III)   | VSR          |
| V+S+T                    | Hard (Type I)     | VSTH         |
| V+S+T                    | Medium (Type II)  | VSTM         |
| V+S+T                    | Soft (Type III)   | VSTS         |

2.2 Configuration of the base case
The base case configuration which is a combination of vertical geometric irregularity and stiffness irregularity, the structure is designed with a stepped shape front view (as shown in figure 1) and all the columns are 3m except the bottom storey columns which are 4m. This induces the stiffness irregularity.

**Figure 1.** Base Case (Combination of Vertical and Stiffness Irregularity)

**Figure 2.** Mass irregularities configuration for three combination irregularities
2.3 Configurations having combinations of 3 irregularities
A total of 9 cases of 3 combination irregularity were assessed by varying the soil types as depicted in table 1. In the case of VSM, mass irregularity has been integrated with base configuration (VS) by amplifying the lumped load on stories 2 & 5 by a factor of 2 as shown in figure 2. Further VSR was investigated where the re-entrained corner was considered by inducing plus shape plan as shown in
figure 5. In the case of VST, the torsional irregularity was induced by replacing the rectangular columns by circular columns of diameter 0.4 m as per the locations shown in the T5 diagram (Figure 3).

Table 2. Configurations having a combination of 4 irregularities.

| Nomenclature | Combination |
|--------------|-------------|
| VSM1T1       | VS+M1+T1   |
| VSM1T2       | VS+M1+T2   |
| VSM1T3       | VS+M1+T3   |
| VSM1T4       | VS+M1+T4   |
| VSM1T5       | VS+M1+T5   |
| VSM1T6       | VS+M1+T6   |

2.4 Configurations having combinations of 4 irregularities
In this set of configurations, the base configuration has been integrated with various combinations of mass (M1 - M7 in figure 4) and torsional irregularities (T1- T6 in figure 3). The details of one set of combinations are tabulated in table 2. A total of 42 configurations have been analysed and each of these cases was analysed by keeping the soil type as constant (hard soil). The location and configurations of irregularities in torsion and mass has been depicted vividly in figure 3 and 4 respectively.

![Figure 5. Plan to induce Re-entrant irregularity](image)

3 Results & Discussion
The results obtained from the seismic response assessment of the grouping of 3 irregularities are plotted and contrasted with the base case.
Figure 6 represents the peak base shear of extreme cases with combinations of 3 irregularities which were taken into consideration. Maximum storey displacements amongst the VSM, VSR and VST is observed when structure was analysed in type III soil. Amongst all the 3 irregularity combinations, the highest base shear value is observed for VSMS; where M configuration of mass irregularity is integrated with VS in soft soil and the least base shear is observed for VSRH; where the re-entrained corner was induced to the base case in hard soil. Compared to the base case in the same conditions, a decrease of 0.0042% and 35.06% of peak base shear value was observed for VSMS and VSRH cases respectively. It is evident that integrating various irregularities with the combination of stiffness and vertical irregularity has not created any critical case with respect to base shear; instead, it displayed how irregularities have damped the effect of VS configuration in a structure. The maximum storey displacement amongst the 3 combination irregularities is observed in VSTS. Compared to base case VSS, VST configuration in soft soil depicted an increase of 4.17% in storey displacement for a 3.7% decrease in peak base shear value. VSRH displays the least maximum storey displacement which is observed to have 11.44% lower value, compared to VSH.

Figure 7 represents the maximum storey displacements of extreme cases amongst the 3 irregularity combinations. For all the cases analysed in hard soil, storey displacements are found to be less than the base case configuration (VSH) except VSTH, where T1 configuration of torsion irregularity is integrated with VS configuration. There is an increase of 1.401% in storey displacements of VSTH compared to the base case (VSH). Further, in the case of soft soil, storey displacement was found to be less compared to the base case analysed in soft soil except for VSTS configuration where it is observed that there is a 4.17% in storey displacement. It is also important to acknowledge the
observation that the combination of mass irregularity with vertical and stiffness irregularity has a very minimal effect on storey displacements and peak base shear.

| Configurations | Base Shear (kN) | Max. Displacement (mm) |
|----------------|----------------|------------------------|
| VSMH           | 17357.71       | 280.928                |
| VSRH           | 11272.34       | 248.815                |
| VSTH           | 16698.16       | 284.975                |
| VSM2           | 23582.05       | 387.407                |
| VSRS           | 14412.50       | 354.345                |
| VSTS           | 22709.50       | 403.628                |
| VSH            | 17358.70       | 280.978                |
| VSS            | 23583.05       | 387.450                |
| VSM1T1         | 16582.89       | 278.429                |
| VSM1T2         | 16783.33       | 284.074                |
| VSM1T3         | 16698.05       | 284.975                |
| VSM1T4         | 16971.68       | 286.671                |
| VSM1T5         | 16370.34       | 281.570                |
| VSM1T6         | 16650.63       | 287.367                |
| VSM2T1         | 16582.72       | 278.429                |
| VSM2T2         | 16783.15       | 284.074                |
| VSM2T3         | 16697.88       | 284.976                |
| VSM2T4         | 16971.50       | 286.671                |
| VSM2T5         | 16370.15       | 281.571                |
| VSM2T6         | 16650.45       | 287.368                |
| VSM3T1         | 16582.56       | 278.431                |
| VSM3T2         | 16782.99       | 284.076                |
| VSM3T3         | 16697.73       | 284.977                |
| VSM3T4         | 16971.34       | 286.673                |
| VSM3T5         | 16369.99       | 281.572                |
| VSM3T6         | 16650.29       | 287.369                |
| VSM4T1         | 16582.44       | 278.432                |
| VSM4T2         | 16782.87       | 284.078                |
| VSM4T3         | 16697.60       | 284.979                |
| VSM4T4         | 16971.21       | 286.675                |
| VSM4T5         | 16369.84       | 281.574                |
| VSM4T6         | 16650.14       | 287.371                |
| VSM5T1         | 16582.36       | 278.435                |
| VSM5T2         | 16782.83       | 284.080                |
| VSM5T3         | 16697.53       | 284.982                |
| VSM5T4         | 16971.17       | 286.677                |
| VSM5T5         | 16369.75       | 281.577                |
| VSM5T6         | 16650.06       | 287.374                |
| VSM6T1         | 16582.33       | 278.436                |
| VSM6T2         | 16782.82       | 284.082                |
| VSM6T3         | 16697.50       | 284.984                |
| VSM6T4         | 16971.17       | 286.679                |
| VSM6T5         | 16369.76       | 281.578                |
| VSM6T6         | 16650.07       | 287.376                |
Figure 8 depicts the comparison of extreme cases of 3 irregularity combinations with the various cases having combinations of 4 irregularities. When we consider the various configurations of torsion in combination with mass, stiffness and vertical irregularity it is observed that few configurations have more displacements than the base case configuration in hard soil (VSH). It observed that VSM1T1 (the least storey displacement case) shows a 0.9% decrease in storey displacement compared to the base case. Further, VSM1T3 depicts a very close behaviour to the base case (VSH). Amongst all the cases assessed by varying various configurations of mass and torsion irregularity, VSM1T6 is observed to display the maximum storey displacement value compared to VSH.

Figure 9 represents the variation in storey displacement for various configurations of torsion irregularity by keeping the other set of configurations constant. Unlike the previous graphs depicting storey displacement, in this graph we can notice that for the changes in torsional irregularity configuration there is no significant variation in storey displacements. After assessing the various combinations of different configurations of mass and torsion irregularity it is observed that torsional irregularity has dominance over mass irregularity when they are in combination with stiffness and vertical irregularity.

Table 3 depicts the maximum Base Shear and maximum storey displacement of different configurations that are considered in the current study. It was observed that the cases with 4 irregularities it is evident that as we increase the load in the higher stories there will be a good variation in the base shear. It is observed that the difference between the base shear for the VSM1T1 and VSM2T1 is significant when compared to the difference between VSM6T1 and VSM7T1 and the same thing continues for T2, T3, etc. This might be due to the presence of vertical geometric irregularity. That is, if we can see the front view of the structure that we have taken, the layout looks like a set of stairs means as we move upward, the area of the floor decreases and as the area reduces the effect of multiplication of load in the higher stories is not very significant. So, from this, we can specify with evidence that not all irregularities are harmful to the seismic behaviour of the structure. It completely relies on the way the irregularity is induced and the type of irregularity, so it is always a good practice to keenly analyse the effect of the irregularities both as a combination and individually and then make appropriate decisions in the construction.

4. Conclusions
The structural response of the multi-storied building with various combinations of irregularities is assessed. The outcome signifies that irregularities have a momentous and varying consequence on the structural response depending upon the combinations and locations of the irregularity. The current investigation depicts that the existence of certain irregularities in a particular combination with others does not necessarily amplify the seismic response of a structure, instead, they can dampen the adverse effect of other irregularities. Among all the cases analysed, the configuration with the combination of vertical and stiffness integrated with torsion irregularity (configuration T1) in soft soil has displayed the highest displacement response while the grouping of Vertical and stiffness irregularity integrated with the re-entrained corner in hard soil is observed to display the least displacement response. In this contemporary society, where people give priority to the aesthetic and architectural outlook of a structure by not compromising on the structural stability, these factors need to be taken into consideration.

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