Recent Trends in Civil Engineering & Technology
Volume 1, Issue 1-3 Compilation 2011

Behaviour of Irregular Concrete Buildings under Seismic Forces

Bharati Raj. J[*] *& A. P. Shashikala*
Dept. of Civil Engineering, National Institute of Technology Calicut, Kerala.

ABSTRACT

The study of irregularities in a building is a fundamental parameter controlling the seismic response of buildings. From the past history of earthquakes, it is evident that the use of improper structural configurations with plan irregularities and soft storeys has decisive effects on the seismic performance of buildings. The buildings with abrupt changes in storey stiffness have uneven lateral force distribution along the height, which is likely to locally induce stress concentration. This has adverse effect on the performance of buildings and hence, is to be analysed for dynamic loads and designed carefully. An attempt has been made to arrive at a criterion for optimal seismic performance of irregular concrete buildings by conducting a comparative parametric study on various irregular buildings, considering drift as the crucial parameter affecting building performance and accounting for the stiffness changes induced due to variations in infill percentage.

Keywords: *Dynamic, Irregular buildings, Seismic performance, Infill percentage, Storey drift*

[*]***Author for Correspondence*** E-mail: bharatiraj83@gmail.com; Tel: +91-9895896756

INTRODUCTION

From the various devastating earthquakes occurred in the past, it is evident that there is great need for a thorough understanding regarding factors affecting the seismic performance of a building. The architectural design decisions that influence the seismic performance of the buildings can be classified into three groups including building configuration issues (as a whole), structural system configuration issues (in plan and in elevation) and non-structural architectural components' configuration issues [1]. Among these, building configuration is seen to have a decisive influence on dynamic behaviour and stress concentration in buildings. The building configuration is defined as "the size, shape and proportions of the three dimensional form of the building". Configuration does not refer here simply to the abstract spatial arrangement of the buildings and their components, but to their type, lay-out, fragmentation, strength and geometry, from which certain problems of structural response to earthquakes are derived. This definition includes the nature, size and location of the structural elements, as these are often determined by the architectural design of the building. The definition for configuration is necessary since the seismic performance of a building depends upon the interaction of various structural and non-structural elements [1].

Seismic behaviour of building depends critically on overall geometry. One of the greatest causes of damage to buildings is the use of improper architectural and structural features. Irregularities in height translated into sudden changes in stiffness between adjacent floors concentrate the absorption and dissipation of energy during an earthquake on the flexible floors where the structural elements are overburdened. Irregularities in mass, stiffness and strength of floors can cause torsional vibrations and concentrating forces which are difficult to evaluate. In irregularly shaped floor plans, the wings may be likened to a cantilever built into the remaining body of the building, a point that would suffer smaller lateral distortions than in the rest of the wing. Large concentrations of stress appear in such transition areas, frequently producing damage to the non-structural elements, the vertical structure, and even the diaphragms. In seismic events, these are the cause of abrupt changes in stiffness and mass, producing a concentration of stresses in the floors near the site of sudden change [1].

Building shape is important because it has a decisive influence on the dynamic behaviour (inverse pendulum, soft storey, torsion effects) and on the stress concentration (variations of vertical and horizontal shape). The geometric parameters qualifying the building shape, commonly referred as influence parameters of the seismic behaviour, are the vertical and plan regularity, the symmetry and the compactness. All these aspects are acknowledged by the major codes that provide design criteria penalizing buildings not having regular and compact shape. Penalization can consist of more stringent and detailed evaluation of the response or of a reduction of the allowed ductility factor for taking into account the reduced dissipative capacity. The global shape irregularity can be a negative factor in itself, but most of all, because it affects the structural system. Irregularities in the seismic resistant system are determinant in reducing the good performance under seismic attack and are the factors especially controlled by seismic codes. High concentrations of mass on a given level of the building are challenging issues. This occurs on floors where heavy structures are placed, such as equipment, tanks, store rooms or filing cabinets. The problem is greater when the heavy load is located at a higher level, due to the fact that seismic response accelerations increase upward, increasing seismic forces and the possibility of equipment collapsing and causing structural damage [1].

The common feature observed in most of the structures is that their ground storey is used for parking with few or no filler walls, which results in a top-heavy and soft-ground floor. Sometimes, it may have smaller stiffness resulting in larger deformation and sometimes its lateral strength is weak. In the vertical plane, the most common configuration irregularity is a storey that is weak (less strong) or soft (less stiff), or both, as compared to the storey above. The usual case is a ground storey that is taller or has fewer columns and walls because it is a more open space. The presence of soft storeys can be attributed to the differences in height between floors and the interruption of the vertical structural elements on the floor [3].

RESEARCH SIGNIFICANCE

All improper configurations and unfavourable architectural features lead to poor seismic performance of buildings. Even though, experience shows that buildings with irregularities are prone to earthquake loading, as demonstrated in many earthquake occurrences [4], irregular structures are commonly found in practice. The current codes fall short to provide simplified analytical tools for irregular structures. Moreover, seismic response analysis for irregular structures requires complex analysis due to non-linear and inelastic response, thus making it more difficult than for regular structures. Even though, dynamic analysis is recommended for the design of irregular buildings, such analysis is rarely carried out properly. Also, little contribution has been done towards reducing the adverse effects of soft storeys in buildings. In this context, the study of seismic performance of irregular buildings and the adverse effects of soft storeys becomes essential. The present work tries to arrive at a criterion for optimal seismic performance of irregular concrete buildings by conducting a comparative parametric study on the various infill percentages. An attempt has been made to study the adverse effects of soft storeys on the building performance by performing three-dimensional dynamic analysis on irregular buildings and accounting for stiffness changes induced due to variations in infill percentage.

ANALYTICAL INVESTIGATION

Seven storied buildings with various configurations and infill percentages are modelled and analysed in Staad Pro 2005. Horizontal irregularity has been incorporated by the analysis of various irregular plans. Vertical irregularity has been taken into account by considering the effects of soft storeys (variation in infill percentages) and flexible storeys at the ground level (increase in height from 3.5m to 4m (137.795 to 157.48inches) for parking space) which are ideal representatives of sudden change in stiffness. The buildings models included Rectangular, L, T & Cross shaped structures [Fig: 1]. The buildings are modelled with a floor area of 1100m^2. The L and T shaped buildings are modelled with asymmetrical wings. The cross shaped buildings are modelled as symmetric as well as asymmetric structures. The stiffness contribution of masonry infill [5] is represented as an equivalent compression strut, having the same thickness and modulus of elasticity as the infill panel it represents as per the guidelines in FEMA 306 [2]. The percentage infill in the building was altered by changing the parameters of the equivalent strut that represented the infill.

Dynamic analysis has been performed by using the Time History Method. Time History Analysis is the analysis for the dynamic response of a structure at each increment of time, when its base is subjected to a specific

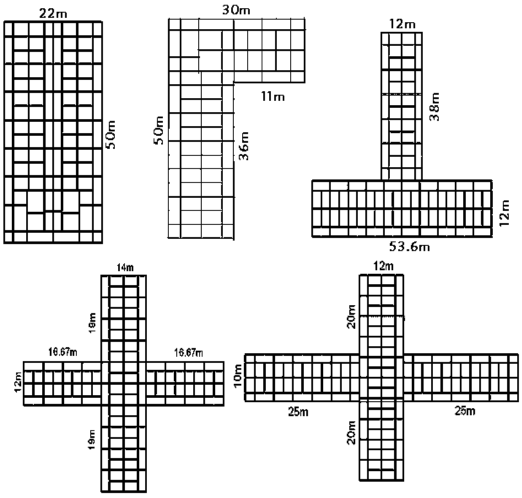

Fig. 1: Plan of the modelled buildings

ground motion time history. The time history of the El Centro (Imperial Valley) Earthquake of 18 May 1940, which led to a total estimated damage, of about $6 million, has been taken as the analysis input data. The magnitude of the earthquake was 7.1. The dynamic analysis is performed on all the models so as to obtain the inter-storey drift. The obtained analysis results are used to conduct a parametric study.

PARAMETRIC STUDY - INTER STOREY DRIFT

The inter storey drifts play a crucial role in determining the response of the building. Hence, the inter storey lateral displacement has been obtained from the dynamic analysis of the various buildings.

The maximum drift values for bare frame buildings and infilled buildings are tabulated in Fig: 2.

The results clearly indicate the inefficiency of L-shaped buildings when compared to the other configurations. The presence of flexible and soft ground storeys drastically enhances the lateral displacement in the buildings, resulting in poor seismic performance of the structures.

The buildings have been categorised according to the percentage of infill in the building. The building is said to be highly permeable when the infill percentage is less than 25% (percentage openings is greater than 75%), less permeable when the percentage infill is greater than 75%. and medium permeable when the infill percentage is between 25 to 75%.

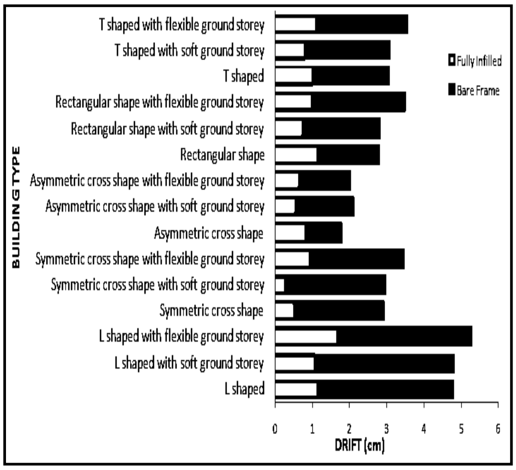

Fig. 2: Maximum Drift values for various buildings

The variation of drift with the storey height for various infill percentages has been plotted for all the modelled buildings. This has been analysed and plotted as drift versus the height curves [Fig: 3-5]. The plotted results are used to evaluate the general response of the buildings under seismic forces.

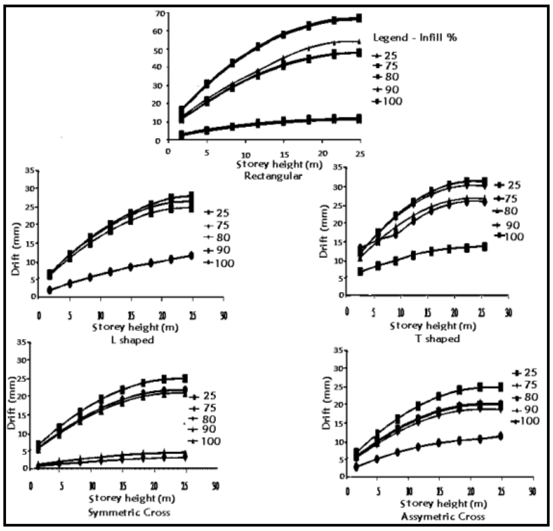

Fig. 3: Variation of storey drift with building height

The evaluation of the storey drift with height reveals that the cross shaped and rectangular shaped buildings have higher seismic performance. The cross shapes perform better due to the larger number of lateral resisting elements in the structure. The rectangular shape is simpler, compact and more or less regular. Therefore, the performance is enhanced. The L shapes and T shapes are more vulnerable to seismic forces due to the sudden change in the orientation of the lateral resisting elements. The increase in infill percentage is found to have negligible effect on the storey drift when irregularities in the building are more prominent.

When the buildings are less permeable, the performance of various configurations is found to remain the same. As the infill percentage is increased beyond 75%, the building becomes stiffer. It is observed that this increase in percentage infill results in no advantageous change in the performance of the irregular buildings; instead a slight increase in the drift is noticed. This throws light on the fact that the addition of infill beyond a certain limit would result in an increase in mass of the structure and hence, adversely affects the seismic performance.

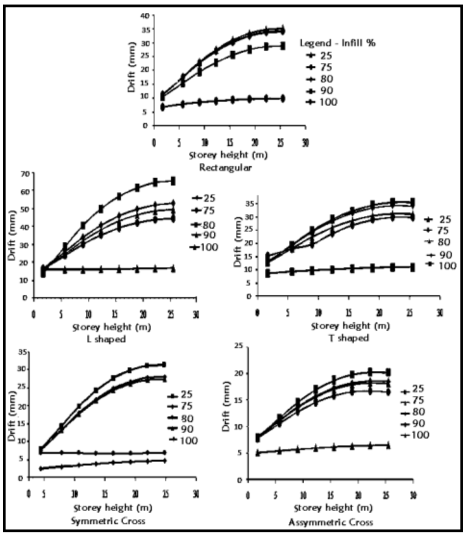

Fig. 4: Variation of storey drift with building height for soft ground storied buildings

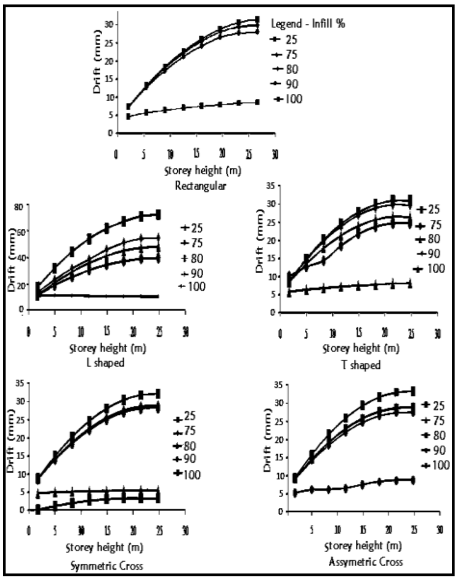

Fig. 5: Variation of storey drift with building height for flexible ground storied buildings

The study of the variation of drift with respect to height indicates that the buildings would have a better seismic performance, when the infill percentage is medium. The increased percentage infill would lead to increase of mass of the structure and hence, reduce the performance. The medium percentage of infill in the buildings proves advantageous as it enhances the resisting capacity of the building and thereby, reduces the drift occurring in the structure.

The irregular buildings are more vulnerable to seismic forces due to the sudden change in the orientation of the lateral resisting members. The increase in the infill percentage in such buildings is found to have an adverse effect on the seismic performance. The increase of infill percentage beyond 80% results in an increase in the drift in the building. The addition of infill contributes to the seismic weight of the building rather than to the lateral stiffness of the structure and thereby adds on to the drift in the building. The sudden change in the storey stiffness; idealised by the buildings having soft storeys and flexible storeys, results in further enhancement in the drift in the storeys making the situation more critical. In this case also, the medium addition of infill reduces the rate of deformation in the building, resulting in better seismic performance.

EVALUATION OF MODE SHAPES

The seismic forces exerted on the building are not externally developed forces like wind. Instead, they are the response of cyclic motions at the base of a building causing accelerations and hence, inertia force. The response is therefore essentially dynamic in nature. The most important dynamic property of the structure is its mode shape, which play a crucial role in determining the response of the building.

The various mode shapes exhibited by the various buildings are described [Fig : 6-10].

It is clearly evident that for a bare framed rectangular building, the collapse mechanism starts after the third mode. In the first three modes, the building exhibits only lateral displacements. The concept of a building being fully infilled is a theoretical case. For such a building, even though the displacements are low due to larger stiffness, the possibility of collapse is greater in all the modes, due to the additional weight contributed by the infill material. Hence, such a building is highly vulnerable to earthquakes.

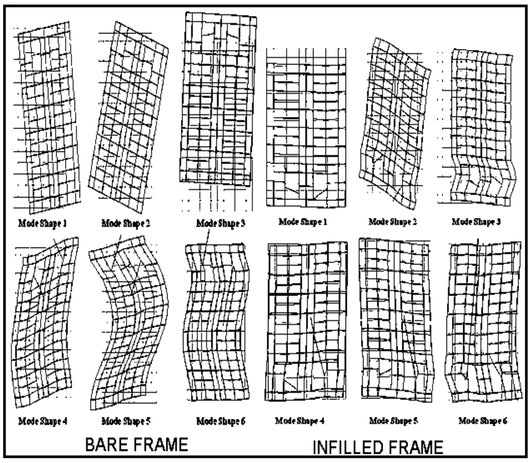

Fig. 6: Mode Shapes for a Rectangular Building

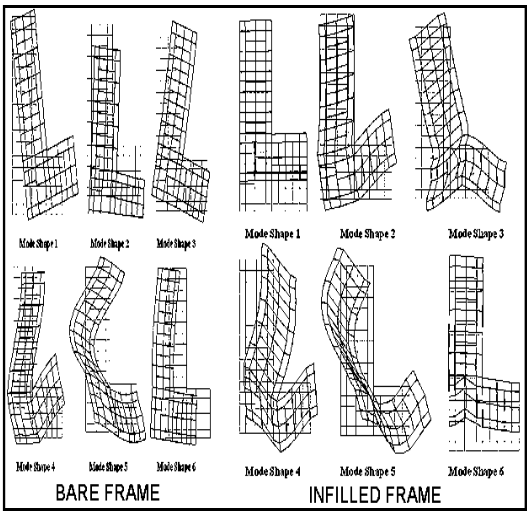

Fig. 7: Mode Shapes for an L-shaped Building

For a bare framed L shaped building, the collapse of the building is initiated at the fourth mode. The building shows only lateral deformations till the third mode. For fully infilled L shaped building, the seismic response is similar to the fully infilled rectangular building. This structure shows a greater tendency to collapse at almost all the modes, due to the infill contributing to the mass of the structure rather than the seismic resistance of the building.

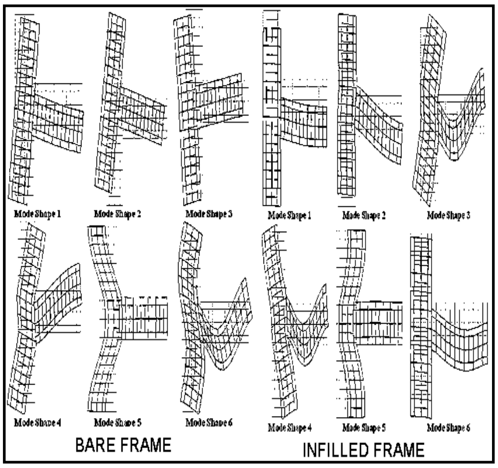

Fig. 8: Mode Shapes for a T-shaped Building

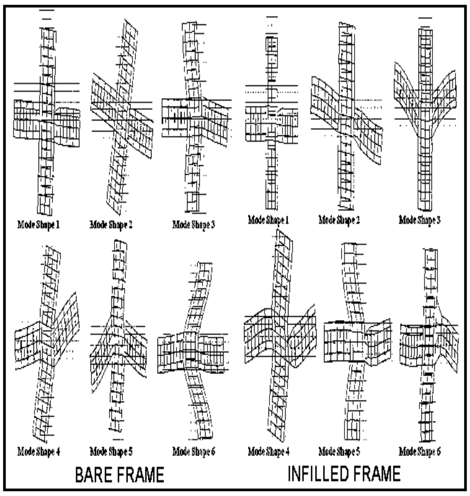

Fig. 9: Mode Shapes for a Cross-shaped Building

The T shaped building shows the tendency to collapse after the third mode. The lateral deformations persist till the third mode. When the T shaped building is made more stiffened by addition of infill, it is seen that the tendency to collapse is not altered. But, there is a reduction in the rate of deformation in the structure.

The fully infilled cross shaped building does not show a tendency to collapse even at higher modes of vibration. This is mainly due to the larger number of lateral resisting elements in the structure. When compared to all the other irregular configurations, the cross shaped is observed to be the most seismically resistant configuration based on the modes shapes exhibited.

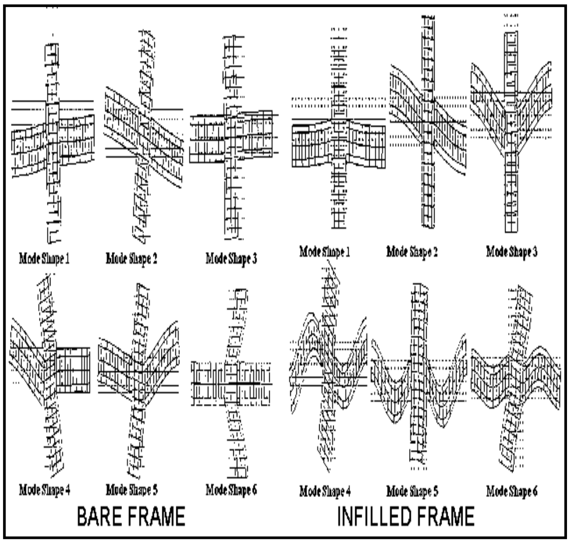

Fig. 10: Mode Shapes for an Asymmetric Cross-shaped Building

FORMULATION OF DRIFT EQUATION

The parametric study very well sheds light on the influence of the basic building configuration, infill percentages and stiffness variations on the drift in the building. In order to arrive at a relation for the relative lateral displacement (drift) in buildings, it is important to identify the above parameters in the building. The existing code provisions accounts the height of the building alone as the basic parameter controlling the drift in the building. Here, in addition to the height, various other parameters including length *L*, width *B*, height *H*, of the building; percentage infill in a single panel of the building frame, *p* and percentage infill in each storey of the building, *P* have also been taken into account.

The first three parameters, *L*, *B* and *H* form the basic dimensions of a building. These dimensions largely determine the way in which the seismic forces are distributed throughout the building and also influence the relative magnitude of those forces. The length and the width of the building account for the horizontal irregularities in the building. The increase in height of a building affects its time period. As a building grows taller, its time period tends to increase and a change in the time period indicates a change in the seismic response of the building. Hence, the height of the building is also considered as a crucial parameter. The presence of masonry infill in the frames of a building alters the behaviour of the building under earthquake type lateral loads. Specifically it changes the strength and stiffness of the structure. The addition of infill considerably increases overall strength and lateral resistance of the building and results in a reduction in the side sway of the overall structure. Infill increases the energy dissipation capacity of buildings, through cracking of infill and friction between infill and surrounding frame. Well constructed infill walls can decrease the probability of collapse of a building. The addition of infill substantially reduces the bending moment in the frame members. Hence, the effect of the masonry infill in the building is taken into account through the fourth parameter, *p*. It is a measure of height-ratio introduced to quantify the extent of irregularity in the building. Height ratio (h_r) is given as the ratio of the height of the opening (h_o) to the height of the storey (h). It is assumed that for a particular height ratio, the masonry infill produces uniform opening size across all bays in the storey.

$$p = 1 - h_r \qquad (1)$$

A soft storey is a storey which shows a significant decrease in the lateral stiffness from the immediately above storey. IS: 1893 (Part 1) : 2002 defines a soft storey as a storey in which the lateral stiffness is less than 70% of that in the storey above or less than 80% of the average lateral stiffness of the three storeys above. The condition of soft storey becomes critical when it is formed in the first storey, since the forces are generally greatest at this level. The essential characteristic of a ground soft storey is a discontinuity of stiffness occurring at the second storey connections. This discontinuity is caused due to the lesser strength or increased flexibility in the first storey and results in extreme deflections in the first storey along with a concentration of forces at the second storey connections. If all the storeys are approximately of the same strength, the entire building deflection under earthquake loads is distributed approximately equally to all the storeys. The last parameter, *P*, is a representative of the soft storeys, which forms the vertical irregularities in the building. It is an estimate of the soft storey height ratio (h_{sr}) defined as the ratio of height of all soft storeys (h_s) to the total height (H) of the building.

$$P = 1 - h_{sr}\, h \qquad (2)$$

All the parameters chosen as the design parameters are assumed as independent variables. Hence, considering drift in the building as a non-linear function of the design parameters, equation for drift in an infilled frame is formulated using Multiple Linear Regression method as:

$$D_{\inf} = 0.00014 \frac{H^5}{L.B^{0.65} p^{0.4} P^{0.2}} \qquad (3)$$

The drift values were re-calculated using the formulated equation and it was seen that the obtained equation shows an average variation of merely 1.0% from the actual input values. It is also clear that the formulated equation predicted the drift values with a better factor of safety as most of the values are over-estimated [Fig: 11]. The formulated equation has a correlation coefficient of 0.602.

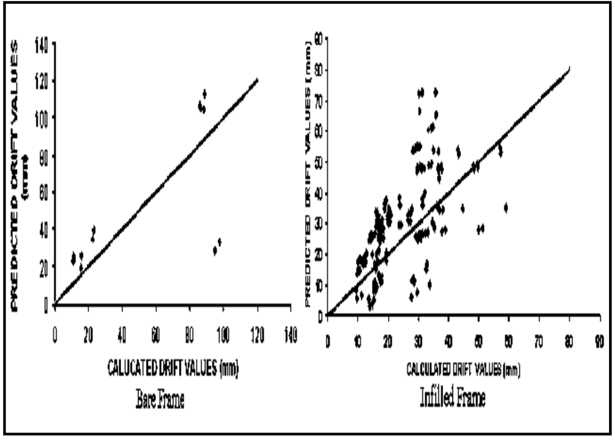

Fig. 11: Validation of the Formulated Equation

An attempt to study the effect of infill in the buildings is also made and a comparative study with buildings modelled as bare frames has been carried out. The buildings modelled as infilled frames have been analysed as bare frames and an equation has been formulated for a bare frame from the analysis results as:

$$D_{bare} = 16800 \frac{H}{L.B^2} \qquad (4)$$

The equation formulated for bare frame shows a correlation coefficient of 0.685 and has an average variation of 1.7%. This equation also over-estimates the drift values. By combining equations (3) & (4), we can arrive at a relation between infilled frame and the bare frame.

$$D_{\inf} = \left(\frac{1}{120 \times 10^{6}} \frac{H^{4} B^{1.35}}{p^{0.4} P^{0.2}} \right) D_{bare} \qquad (5)$$

From the above relation, it can be concluded that the presence of infills in a building leads to a considerable reduction in the drift occurring in the building. The drift in a bare frame would be decreased by a factor of $\left(\frac{1}{120 \times 10^{6}} \frac{H^{4} B^{1.35}}{p^{0.4} P^{0.2}} \right)$.

Both these formulated equations can be used to calculate the drift in irregular buildings with an average accuracy of around 98%. In most cases, the maximum lateral displacement at the roof level (drift) has been over estimated.

OPTIMISATION OF SEISMIC PERFORMANCE

The objective of the optimization problem is to maximize the seismic performance of the irregular building. In this work, seismic performance has been related to the drift occurring in the building under earthquake loads. Hence, the building will exhibit maximum performance when the drift occurring is a minimum. The criterion for optimal seismic performance is obtained by minimising the drift occurring in the building, formulated as an unconstrained minimization problem. Among the various methods available for unconstrained optimization, a pattern search method known as Hooke and Jeeves' method has been adopted for solving the optimization problem.

$$X_1 = \begin{Bmatrix} L_1 \\ B_1 \\ H_1 \\ p_1 \\ P_1 \end{Bmatrix} = \begin{Bmatrix} 20 \\ 10 \\ 10 \\ 0.25 \\ 0.1 \end{Bmatrix}$$ and, the incremental value,

$$\Delta X = \begin{Bmatrix} 0.5 \\ 0.5 \\ 0.25 \\ 0.1 \\ 0.01 \end{Bmatrix}$$

The iteration is started by assuming the design parameters in such a way that the length to breadth ratio of the building varied from 2.00 to 5.00. The optimization process is carried out for different heights from 10m (typical three storey building) to 28m (typical eight storey building). The percentage infill values are assumed as minimum for the starting value. The building is considered to be having 100% of soft storeys for the first trial.

The explanatory move is carried out by assuming a minimal incremental value. The explanatory move clearly indicated that the direction of search is in a positive direction for all the design parameters. Hence, the length, width, height and the percentage infill are increased, while the soft storey percentage is decreased (i.e. the parameter, P is increased). The trial values are assumed for varying heights and length to width ratios and thus 85 trial values are assumed in the optimization problem. The pattern search move is executed after finding the correct direction of search.

This pattern search method is performed as iteration in the Newton Raphson Method. A total of 500 iterations are carried out in the pattern search move for each of the length to breadth ratio, so as to arrive at reliable results.

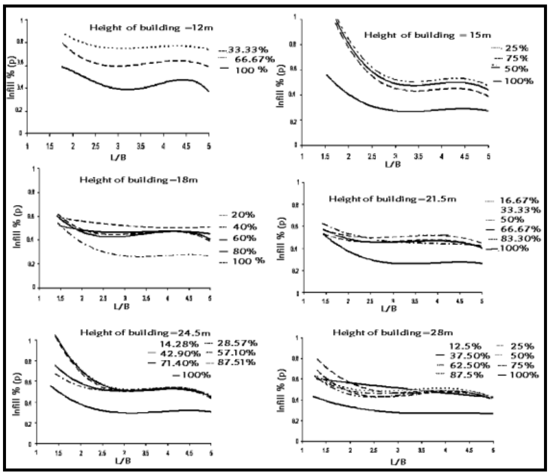

Fig. 12: Design curves for optimum infill percentages

The results obtained after optimization has been plotted as design curves of the length to breadth ratio (L/B) versus the percentage infill, for varying heights and varying soft storey percentages [Fig: 12]. These curves enable the selection of the optimum percentage of infill for any length to breadth ratio ranging from 2.00 to 5.00 for various heights and soft storey percentages.

The plotted curves show that the irregular buildings exhibit a very complex response under earthquake loading. For L/B ratios up to 2.00, the building can be considered more or less as a regular building. The percentage infill required for maximum seismic performance is seen to be reducing for these L/B ratios. After that, the percentage infill remains almost steady up to 3.00, beyond which, the required percentage infill shows a slight increase. This indicates that the resisting capacity of irregular buildings can be enhanced by providing more infill to the structure. But, as the L/B ratios reach 4.00, there is a sudden decrease in the infill percentage. This clearly points out the disadvantageous nature of infill in irregular buildings. When the percentage of infill is increased in buildings having greater horizontal irregularities, the infill adds on to the mass of the building, instead of the lateral stiffness of the building and result in an adverse effect on the seismic performance of the building. Hence, for L/B ratios greater than 4.00, the percentage infill is to be reduced. As the height of the buildings increase, the curves drawn for various soft storey percentages are found to coincide at 50% infill for L/B range of 3.00 to 4.00. From this, it can be understood that for irregular buildings having a configuration ratio beyond this range, the addition of infill beyond 50% would result in an adverse effect on the seismic performance.

SUMMARY & CONCLUSIONS

Based on the dynamic analysis conducted the seismic performance of irregular buildings has been successfully evaluated and conclusions are arrived.

1. A detailed study of the various parameters obtained from the dynamic analysis

indicated that the drift occurring in the building is the most crucial measure of the building seismic performance. The inter-storey drift depends on various factors such as the building configuration and the infill percentage.

2. An empirical relation between building configuration, infill percentage and the storey drift has been derived for bare frames and infilled frames. Both these formulated equations can be used to calculate the drift in irregular buildings with an average accuracy of 98%.
3. The optimisation of the infill percentage for buildings has been carried out. Design curves have been proposed to arrive at suitable building configurations and infill percentage for maximum seismic performance based on the height and stiffness irregularities of the building.
4. The irregular buildings have a complex behaviour under seismic forces. They show a tendency to collapse at higher modes of failure. Rectangular shapes are compact, simple and more or less regular. Hence, the performance is more even in the presence of flexible storeys.
5. The Cross Shaped building shows the best seismic performance due to the presence of larger number of lateral resisting members in the load direction. The L shaped buildings proves to be the least seismically resistant structure due to the highly irregular orientation of the lateral resisting members.
6. The addition of infill to irregular buildings proves advantageous in reducing the drift in the building only to a certain extent. The building, when made highly impermeable, adversely affects the seismic performance by adding to the seismic weight of the building. The performance of irregular buildings is seen to be better for medium permeability. Hence, infill is to be restricted to 50-80% so as to obtain effective performance.
7. In irregular buildings with building configuration ratio higher than 3.00, it is found that the increase of infill beyond 50% would have absolutely no advantage on the performance of the building. Instead it would add up to the seismic weight and end up in poor performance.

REFERENCES

1. Arnold C. & Reitherman R. *Building configuration and seismic design* NY. Wiley. 1982. 296p.
2. FEMA 306. *Evaluation of earthquake damaged concrete and masonry wall buildings* Basic Procedures Manual. 1998.
3. Murty C. V. R., Jaswant N. & Sudhir K. J. *Seismic Response of RC Frame Buildings with Soft First Storeys* Proceedings of the CBRI Golden Jubilee Conference on Natural Hazards in Urban Habitat. 1997.
4. Özmen C. & Ünay A. I. “Commonly encountered seismic design faults due to the architectural design of residential buildings in Turkey” *Building and Environment* Elsevier. September, 2005.
5. Stafford S. B. “Lateral stiffness of infilled frames” *Journal of the Structural Division (ASCE*) 1962. 88(6)