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Seismic Effects on Irregular Buildings- State of the Art

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***Abstract*:-** Irregular buildings constitute a large portion of the modern urban infrastructure. The group of people involved in constructing the building facilities, including owner, architect, structural engineer, contractor and local authorities, contribute to the overall planning, selection of structural system, and to its configuration. This may lead to building structures with irregular distributions in their mass, stiffness and strength along the height of building. When such buildings are located in a high seismic zone, the structural engineer's role becomes more challenging. Therefore, the structural engineer needs to have a thorough understanding of the seismic response of irregular structures. In recent past, several studies have been carried out to evaluate the response of irregular buildings. This paper is an attempt to summarize the work that has been already done pertaining to the seismic response of irregular building frames.

Keywords:- *Torsion, mass irregularity, stiffness irregularity, setbacks*

I. INTRODUCTION

It is always the greatest challenge for structural engineers to design structures capable of withstanding lateral forces due to wind and earthquake. Uncertainties involved and behavior studies are vital for all civil engineering structures. Building architecture has also changed drastically with the changing/varying exterior massing arrangements and shapes. Many buildings are now asymmetric in plan and/or in elevation based on the distribution of mass and stiffness along each storey throughout the height of the building. Most recent earthquakes have shown that the irregular distribution of mass, stiffness and strengths may cause serious damage in structural systems. However an accurate evaluation of the seismic behavior of irregular buildings is quite difficult and a complicated problem. Due to the variety of parameters and the choice of possible models for torsionally-unbalanced systems, there is as yet no common agreement or any accurate procedure advised by researchers on common practice in order to evaluate the torsional effects. Seismic damage surveys and analyses conducted on modes of failure of building structures during past severe earthquakes concluded that most vulnerable building structures are those, which are asymmetric in nature. Asymmetric building structures are almost unavoidable in modern construction due to various types of functional and architectural requirements.

II. DESIGN CONSIDERATIONS IN SEISMIC CODES

An asymmetric building structure (torsionally-unbalanced) can be defined as one in which for a purely translational motion, the resultant of the resisting forces does not pass through the centres of mass (Humar and Kumar, 1999). When strained into the inelastic range, torsional motions in such structures will lead to displacements and ductility demands much larger than those in symmetric buildings (torsionally-balanced) which have similar characteristics.

In general, the torsion arising from eccentric distribution of mass and stiffness can be taken into account by describing an incremental torsion moment (T) in each storey equal to the shear (V)in that storey multiplied by the eccentricity (e), measured perpendicular to the direction of applied ground motion (Fig.1). A precise evaluation of the torsion response is quite complicated because the coupled lateral torsion vibration modes of the entire structure are to be considered by performing a two or three dimensional response calculations. As an approximation, the torsion moment in each storey can be obtained by summing from the top storey the incremental torsion moments.

Torsional effects may significantly modify the seismic response of buildings, and they have caused severe damage or collapse of structures in several past earthquakes. These effects occur due to different reasons, such as no uniform distribution of the mass, stiffness and strength, torsional components of the ground movement, etc. In ductile structures, the main consequence of floor twist is an unequal demand of lateral displacements in the elements of the structure. As a result, the lateral ductility capacity of the system may be smaller than the lateral ductility capacity of the elements. Design codes incorporate special requirements to take into account the torsional effects, which usually imply the amplification of eccentricity and the consideration of an accidental eccentricity. These requirements are mainly based on elastic considerations developed several decades ago.

The static torsion responses in each storey are determined by computing the twist in each storey obtained by dividing

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the total torsion storey moment by the storey rotational stiffness. These twists are then added from the base upward to obtain the total twisting or torsion response at each floor level. Since these are static responses, they should be amplified for dynamic response using the response spectrum amplification factor for the fundamental torsion frequency of the structure. However in many design codes, responses are not amplified. Accidental torsion may arise in many ways. Most current codes use accidental eccentricity value of 5% of the plan dimension of the storey perpendicular to the direction of applied ground motion. The accidental torsion may be considered as an increase and also as a decrease in the eccentricity. Corresponding to the distance between the centre of mass and centre of resistance in various storeys, with considerations of increases in all levels or decreases in all levels, two bounding values are obtained.

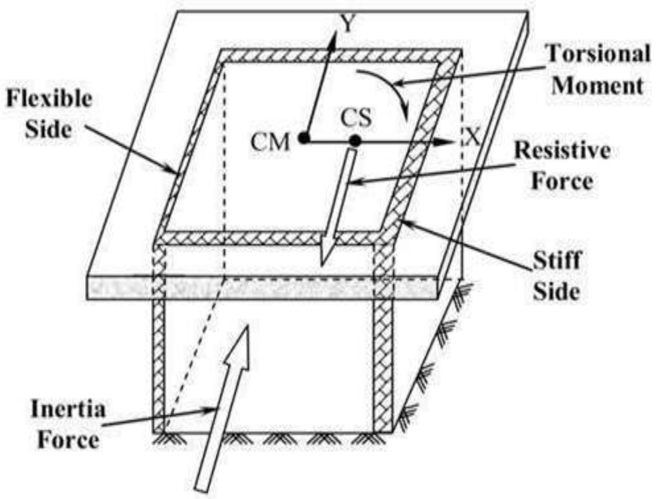

Fig. 1 Generation of torsional moment in asymmetric structures during seismic excitation (Ref: Sachin G Maske, Dr P S Pajgade, Torsional behavior of asymmetric buildings, *IJMER*)

The eccentricity of the centre of stiffness from the centre of mass is found from

$$e_{Rx} = \frac{\sum_{i=1}^{n} k_{yi} x_i}{\sum_{i=1}^{n} k_{yi}} \quad \text{and} \quad e_{Ry} = \frac{\sum_{j=1}^{m} k_{xj} y_j}{\sum_{j=1}^{m} k_{xj}}$$

where k_{yi} and k_{xj} are the stiffness of frames in the y- and x- directions respectively, and x_i and y_j , the respective distances measured from the centre of mass.

The eccentricity of the centre of strength from centre of mass is given by

$$e_{Vx} = \frac{\sum_{i=1}^{n} V_{yi} x_i}{\sum_{i=1}^{n} V_{yi}} \quad \text{and} \quad e_{Vy} = \frac{\sum_{j=1}^{m} V_{xj} y_j}{\sum_{j=1}^{m} V_{xj}}$$

where V_{yi} and V_{xj} are the design base shear strengths of frames in the y- and x- directions, respectively. Torsional response of asymmetric structures responding to seismic excitation is complex involving both strength and stiffness eccentricities as well as torsional mass inertia (Priestley et al., 2007). Peak response displacements at opposite sides of an asymmetric building do not occur simultaneously nor do they correspond to peak torsional response. As such, it is not possible to provide exact analytical methods appropriate for simple preliminary design. Maximum displacement of an asymmetric building can be calculated as the sum of direct and torsional components of displacement. The displacements Δ_1 and Δ_2 of the stiff and flexible sides can be obtained by knowing the translational displacement of C_M and the twist angle θ which is given by

$$\theta = \frac{V_{By} e_{Rx}}{J_{R,eff}}$$

$$J_{R,eff} = \frac{1}{\alpha} \sum_{i=1}^{n} k_{el,yi} (x_i - e_{Rx})^2 + \sum_{j=1}^{m} k_{el,xj} (y_j - e_{Ry})^2$$

The transverse elements are expected to remain elastic or nearly elastic and hence their stiffness is not reduced.

III. FEATURES THAT AFFECT THE RESPOSE OF BUILDING DURING EARTHQUAKE

The behaviour of a building during earthquakes depends critically on its overall shape, size and geometry, in addition to how the earthquake forces are carried to the ground. Hence, at the planning stage itself, architects and structural engineers must work together to ensure that the unfavourable features are avoided and a good building configuration is chosen. The wide range of structural damages observed during past earthquakes across the world is very educative in identifying structural configurations that are desirable versus those which must be avoided.

Size of Buildings: In tall buildings with large height-to-base size ratio, the horizontal movement of the floors during ground shaking is large. In short but in very long buildings, the damaging effects during earthquake shaking are many. And, in buildings with large plan area like warehouses, the horizontal seismic forces can be excessive to be carried by columns and walls (Fig. 2).

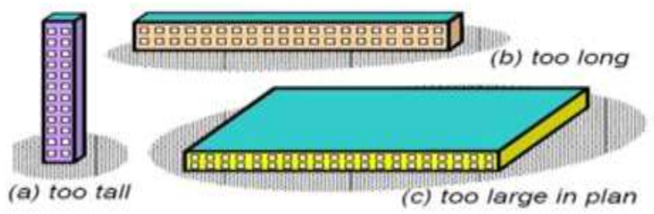

Fig.2 Buildings with one of their overall sizes much larger or much smaller than the other two sizes (Courtesy: CVR Murty)

Vertical Layout of Buildings: The earthquake forces developed at different floor levels in a building need to be brought down along the height to the ground by the shortest path; any deviation or discontinuity in this load transfer path results in poor performance of the building. Buildings with vertical setbacks (like the hotel buildings with a few storeys wider than the rest) cause a sudden jump in earthquake forces at the level of discontinuity (Fig.3). Buildings that have fewer columns or walls in a particular storey or with unusually tall storey, tend to damage or collapse which is initiated in that storey. Many buildings with an open ground storey intended for parking collapsed or were severely damaged in Gujarat during the 2001 Bhuj earthquake. Buildings on sloping ground have unequal height columns along the slope, which causes ill effects like twisting and damage in shorter columns. Buildings with columns that hang or float on beams at an intermediate storey and do not go all the way to the foundation, have discontinuities in the load transfer path. Some buildings have reinforced concrete walls to carry the earthquake loads to the foundation. Buildings, in which these walls do not go all the way to the ground but stop at an upper level, are liable to get severely damaged during earthquakes.

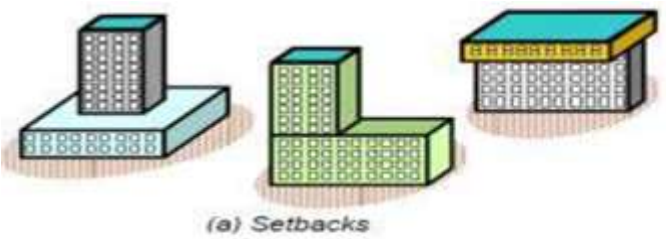

Fig.3 Vertically Irregular Buildings (Courtesy: CVR Murty)

Open-ground storey (OGS) buildings are common in India, because they provide large parking space, which is a major requirement for buildings in urban areas. But, it was found that many buildings that failed during 2001 Bhuj earthquake were of this type. Collapse of these buildings is predominantly owing to the formation of soft or weak storey mechanisms in the ground storey columns. The sudden reduction in lateral stiffness, strength and mass in the ground storey, results in higher stresses in the ground storey columns under seismic loading (Davis, 2009).

IV. CAUSES OF TWIST IN BUILDINGS DURING EARTHQUAKES

When irregular features are included in buildings, a considerably higher level of engineering effort is required in the structural design and yet the building may not be as good as one with simple architectural features. Decisions made at the planning stage on building configuration are more important, or are known to have made greater difference, than accurate determination of code specified design forces.

A building with identical vertical members and that are uniformly placed in the two horizontal directions, when shaken at its base in a certain direction, swings back and forth such that all points on the floor move horizontally by the same amount in the direction in which it is shaken.

If the mass on the floor of a building is more on one side (for instance, one side of a building may have a storage or a library), then that side of the building moves more due to ground movement (Fig. 4). This building moves such that its floors displace horizontally as well as rotate.

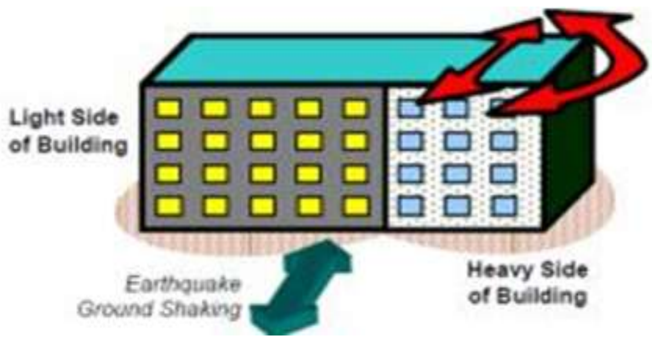

Fig. 4 Mass eccentricity in buildings (Courtesy: CVR Murty)

Buildings that are irregular shapes in plan tend to twist under earthquake shaking. For example, in a propped overhanging building, the overhanging portion swings on the relatively slender columns under it. The floors twist and displace horizontally.

V. LATEST RESEARCH WORKS ON ASYMMETRIC BUILDINGS

S. G. Maske and P S Pajgade (2013**)** studied the influence of the torsion effects on the behavior of the structure. Two cases are considered for the study. Case one is without considering torsion and case two is considering torsion. The Indian standard code of practice IS-1893 (Part I: 2002) guidelines and methodology are used for analysis and design. Results are compared in terms of % Ast in columns. They conducted the structural analysis and design of four storey reinforced concrete asymmetric frame building with the help of Etab software.

S.A. A. A. Rahman and G. Deshmukh (2013) studied the proportional distribution of lateral forces evolved through seismic action in each storey level due to changes in stiffness of frame on vertically irregular frame. As per the Bureau of Indian Standard (BIS) 1893:2002(part1) provisions, a G+10 vertically irregular building is modeled as an simplified lump mass model for the analysis with stiffness irregularity at fourth floor. They studied the response parameters like story drift, story deflection and story shear of structure under seismic force under the linear static & dynamic analysis. The analysis focused on the base shear carrying capacity of a structure and performance of structure. They concluded that a building structure with stiffness irregularity provides instability and attracts huge storey shear. A proportionate amount of stiffness is advantageous to control over the storey and base shear.E Tab was used for modeling and analysis.

B.G.N. Kumar and A. Gornale (2012) studied the performance of the torsionally balanced and unbalanced buildings also called as symmetric and asymmetric buildings subjected to pushover analysis. The buildings have unsymmetric distribution of stiffness in storeys. Also studies are conducted on the effect of eccentricity between centre of mass (CM) and centre of story stiffness (CR) and the effect of stiffness of infill walls on the performance of the building. It is concluded that the analytical natural period depends on the mass and stiffness of each model and is therefore different for models with different amounts of eccentricity and where stiffness of infill walls is considered or ignored. It can be observed that models where stiffness of infill walls is considered to have significantly lower fundamental natural period as compared to models where stiffness of infill walls ignored. This is to be expected, and is mainly due to the stiffness contribution of the diagonal struts in models where stiffness of infill walls is considered.

Q. Z. Khan, A. Tahir and S. S. Mehboob (2013) studied the performance evaluation of reinforced concrete buildings with vertical irregularities (i.e., setbacks). A five story vertically regular building is designed by equivalent static load method of seismic analysis by using UBC (Uniform Building Codes) 1997. Nine vertically irregular models are derived from the regular building by omitting different stories at different heights creating setbacks. For numerical solution ETABs nonlinear version software is used. Time history and response spectrum analysis are performed for ground acceleration data of earthquake. The study as a whole is a slight attempt to evaluate the effect of vertical irregularities on RC buildings, in terms of dynamic characteristics such as story displacement, overturning moment, base shear, story drift and participating mass ratio. Time history analysis and response spectrum analysis are performed for each of x-x and y-y directions and performance level of the buildings are obtained. The response of the superstructure is assumed to be linear elastic. The dynamic numerical analysis is carried out by using ETABS computer software. Seismic performance assessment of the derived vertically irregular buildings has been realized by 3D modeling of the frame structure by introducing elements in ETABS software. They concluded that the irregularity established due to setbacks, that even very large variation of irregularity distribution in elevation causes reasonable modifications of the seismic response with respect to the reference regular case. Maximum story drift and story displacement will increase as the vertical irregularities increase inmodels. The structural and architectural configurations should be observed keenly to attain the optimum performance of the building in terms of its seismic response.

N. P Modakwan, S. S Meshram and D. W. Guwatre (2014) studied the different irregularity and torsional response due to plan and vertical irregularity in buildings and analyzed cross shape and L shape buildings while earthquake forces acts and calculated the additional shear due to torsion in the columns.It is concluded that the re-entrant corner columns are needed to be stiffened for shear force in the horizontal direction perpendicular to it as significant variation is seen in these forces. Significant variation in moments, especially for the higher floors about axis parallel to earthquake direction, care is needed in design of members near re-entrant corners. From the torsion point of view the re-entrant corner columns must be strengthen at lower floor levels and top two floor levels and from the analysis it is observed that behavior of torsion is same for all zones.

A number of parameters govern the response of asymmetric buildings, but the one that has the most significant effect is the torsional stiffness (M/θ) (Humar and Kumar, 1999). Even though the torsional stiffness changes continuously as the structure enter into the inelastic region, it is the elastic

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torsional stiffness that influences the response. It is to be noted that all in-plane structural elements (both parallel and perpendicular to the earthquake motion) contribute to the torsional stiffness. On the basis of analytical studies on elastic and inelastic behaviour, they concluded that the most important parameter governing the torsional response is the ratio of uncoupled elastic torsional frequency to the uncoupled elastic translational frequency or equivalently, the ratio of torsional to translational stiffness in the elastic range.

The uncoupled elastic translational frequency and the uncoupled elastic torsional frequency are defined as

$$\omega_y = \sqrt{K_y / m}$$
$$\omega_\theta ' = \sqrt{K_{\theta R} / mr^2}$$

where K_y is the sum of the elastic stiffness of planes in the y-direction and $K_{\theta R}$ is the torsional stiffness about the centre of stiffness. The uncoupled frequency ratio is defined as

$$\Omega_R = \frac{\omega_\theta '}{\omega_y} = \sqrt{\frac{K_{\theta R}}{r^2 K_y}}$$

If N_R is greater than 1, the response is mainly translational and the structure is considered as torsionally stiff; on the other hand, if N_R is less than 1, the response is affected by torsion and the structure is treated as torsionally flexible.

Various researchers conducted analytical and experimental studies on stepped and set-back buildings (where a narrow tower projects from a wide base) and came up with contradictory results which are specific to the building models they had selected. As per Priestley (2007), in buildings which are stepped along one direction only, the stepped frames are not much influenced by the irregularity and only the frames in the perpendicular direction will have some effect due to the stepping. In his opinion, the eccentric mass of the top storeys will induce torsion in bottom portion of buildings and hence a torsional analysis needs to be done for the frames in the perpendicular direction.

The regularity of building can be quantified using regularity/ irregularity indices, based on the geometry of the building. Karavasilis et al. (2008) had proposed two irregularity indices (Φ_s , storey-wise and Φ_b , bay-wise) as follows:

$$\Phi_s = \frac{1}{n_s - 1} \sum_{1}^{n_s - 1} \frac{L_i}{L_{i+1}}$$

$$\Phi_b = \frac{1}{n_b - 1} \sum_{1}^{n_b - 1} \frac{H_i}{H_{i+1}}$$

where n'_s is the number of storeys of the frame and n_b is the number of bays at the first storey of the frame. H_i and L_i are the height and width of the i^{th} storey. However, this does not give a measure of the overall irregularity in the building.

Sarkar et al. (2008) proposed a single regularity index (η) which is based on the dynamic behaviour of the structure and is given below:

$$\eta = \frac{\Gamma_1}{\Gamma_{1,ref}}$$

where Γ_1 is the first mode participation factor for the stepped frame and $\Gamma_{1,ref}$ is the first mode participation for the regular frame without steps. Even though this approach seems to be more logical, one has to do a modal analysis to obtain the regularity index.

Sarkar et al. had also proposed a correction factor (κ) for the code proposed empirical formula for fundamental period of regular building to get that of stepped frame. It is given by,

$$\kappa = \frac{T_{stepped}}{T_{regular}} = 1 - 2(1-\eta)(2\eta - 1) \quad [\text{for } 0.6 \le \eta \le 1.0]$$

VI. SUMMARY

Review of literature on asymmetric buildings reveals that irregularities due to asymmetric distribution of mass, stiffness and strength are sources of severe damage because they result in floor rotations in addition to floor translations. A common form of vertical irregularity arises from reduction of the lateral dimension of the building along its height and such buildings are known as stepped buildings. This building form is becoming increasingly popular in modern multistorey building construction mainly because of its functional and aesthetic architecture. In particular, such a stepped form provides for adequate daylight and ventilation in the lower storeys in an urban locality with closely spaced tall buildings. Vertically irregular buildings (like open ground storey and stepped buildings) are common in India, but are more vulnerable to earthquake shaking. The collapses of irregular buildings during recent earthquakes have raised many questions regarding the adequacy of current seismic provisions to prevent collapse of such buildings. New design methods are needed which can improve the performance of such buildings under expected seismic shaking.

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