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Analysis of the Effects of Vertical Irregularity on Isolated Structures

Anthony Quansah[1], Xiao Zhirong[1]

[1]Zhejiang University of Science and Technology/Sch. of Civil Engineering, Hangzhou, China

Abstract: Vertical irregularity tends to have an adverse impact on the seismic effect on structures, but currently, there is the lack of appropriate research on the use of isolation technique to reduce seismic effect and issues related to a weak story. This paper focuses on the analysis of isolated vertical irregular structure in both scenarios of mass distribution and stiffness distribution. Discussion on the influence of shear forces distribution pattern, damping coefficients and other parameters caused by the irregular distribution of story mass and stiffness is made. According to previous works cited and our case study analysis, it concluded that base isolation of irregular structures ensures better seismic resistance by reducing base shear and improving damping characteristics.

Keywords: Isolated Structure, Vertical Irregularity, Effect

I. Introduction

Post-earthquake damage records have shown that a significant amount of structural failures are due to the presence of vertical irregularities[1] and the unpardonable consequences are the loss of human lives. A. Habibi et al[2] reported that when irregularities occur in elevation, the requirements of the life safety level are not satisfied. Vertical irregular structure refers to structures with irregular lateral stiffness distribution, irregular mass distribution, discontinuity of vertical lateral force resisting members or the sudden change of the bearing capacity of the floor. Specifically, the existence of any of these conditions will results in some respective structural consequences i.e. larger inter-story drifts in the case of stiffness irregular structure and higher base shear in the case of mass irregular structure B. Himanshu[3]. The common issue with all of these kinds of irregularity compared to a regular structure is the significant increase in story displacement which substantially increases the story seismic demands which as a result too leads to a significant reduction in the ductility of the local vertical members to a great extent. A vertical irregularity hence has a negative impact on the response of structures to seismic action.

II. The Research Status of Vertical Irregular Structure

Vertical irregular structure has more complex static and dynamic characteristics. Height-wise changes in stiffness and mass render the dynamic characteristics of these buildings different from the regular buildings [1]. In recent studies, it is clear that seismic performance of this type of structure has become the main focus of research in the field of earthquake engineering. Many experts and scholars through theoretical analysis and numerical simulation, etc., has carried out extensive and in-depth investigations and study, in order to get more conclusions and understanding of these complex dynamic characteristics of irregular structures. A part of the research results has been applied in the much of seismic design of buildings. Previous research work can be categorized in three aspects, i.e. Irregularity limits and its evaluation specification; seismic demands and response of irregular structure; Analytical Approach and its mode of application.

A. *Irregularity Limits And Its Evaluation Specification*

Issues about evaluation specification, vertical irregularity control limits and the effectiveness of the international standards have been talked about in many previous works. Dangyu et al [17] highlighted on some state-of-art been applied in seismic evaluation by Chinese Seismic Code. A similar work was studied by Devesh P. Soni et al [4] but on a basis of vertical irregularities criteria and its evaluation specifications. Guangren Yu et al [5] did a comparison of the USA, Japan and China seismic design procedures and finally concluded that there exists a significant difference in the effectiveness of these standards. Can Song et al[6] studied the similarities and differences between the concept and application of both American code and Chinese code and further disclosed that their analysis results are very close. N.Kara[7] based on numerical

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Anthony Quansah, Xiao Zhirong (Correspondence)
antquansah119084@gmail.com: hafxzr@sohu.com
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analysis techniques to specify a practical limit for irregularity and also determined an acceptable degree of irregularity. One technique applied in N.Kara's research in specifying irregularity limit was by identifying the load path in the structural system.

B. Seismic Demands and Requirements of Irregular structure

A handful research effort has been put in the dimension of seismic response analysis and seismic demands of a vertical irregular structure. Vital seismic demands like ductility demands, deformation demand and energy dissipation demands have been discussed in previous studies. Ductility is the capability of a material to undergo deformation after its initial yield without any significant reduction in yield strength[8].Ductility demands are very complicated to estimate in the case of irregular structures and hence Jing Zhou et al [9] suggested in a study that ductility modification factors somehow accounts for the effects of vertical irregularity and hence should be used to modify the reference regular (multi-degree of freedom) MDOF systems to achieve the irregular ductility demands.

C. Analytical Methods and Mode of Application

Although current research on the seismic performance of a vertical irregular structure is more, but due to the complex seismic response behaviour and its intricate demands, there are some differences in the research methods and core interest for different researchers that attempt this issue. So far, the lack of precise and comprehensive understanding of these complex analytical and numerical methods still continues to be a problem and hence there is the need to continue in-depth study. P. Moehle [10] found in a study that standard limit analysis and static inelastic analysis provide good measures of strength and deformation characteristics under strong earthquake motions.

N. Caterino et al [11] conducted a study on some approximate methods and numerical applications to evaluate the stiffness and inter-story drift response of RC Buildings in seismic Area.

III. Relevant overview of vertical irregular structure

A. Vertical Irregularities Connotation

During the seismic design of buildings, it is required that reasonable choice be made, in terms of the structure plan geometry and vertical arrangement of the facade, during the planning and designing stage as it greatly influences the structural performance during seismic. Usually building shape is often dictated by the site, the program, or other requirements beyond the control of the architect or engineer. Architects are rather advised to provide a regular vertical configuration and uniform shapes such as rectangular and trapezoidal shapes when possible. M. Mohod [12] in a study discussed the effect of shape and plan configuration on structure's seismic response and concluded that a Plus-shape, L-shape, H-shape, E-shape, T-shape and C-shape building suffers more lateral displacement compared to other simple shaped building i.e. regular shape. Hence it is observed that simple plan and configuration must be adopted at the planning stage to minimise the effect of the earthquake. N. Caterino et al[11] highlighted that most recent building codes like Eurocode 8, Italian code OPCM3274, 2003 discourage design of irregular buildings. In the cases where irregular shapes are unavoidable, the portions of the building can be separated with a seismic joint to minimise the problem. The Irregular vertical structure type is mainly categorised in the following points, namely:

1) Irregular lateral stiffness(soft story).

A soft story is one in which the lateral stiffness is less than 70 percent of that in the story above or less than 80 percent of the average stiffness of the three stories above.[18].

2) Extreme soft story

An extreme soft story is one in which the lateral stiffness is less than 60 percent of that in the storey above or less than 70% of the average stiffness of three storeys above.[13]

3) Mass irregularity

These are considered to exist where the effective mass of any storey is more than 150% of the effective mass of an adjacent storey. The effective mass is the real mass consisting of the dead weight of the floor plus the actual weight of partition and equipment.

4) Discontinuity in Capacity.

One in which the story lateral strength is less than 80 percent of that in the story above. The story strength is the total strength of all seismic –resisting elements sharing the story shear for the direction under consideration.

5) Vertical geometric irregularity

Geometric irregularity exists when the horizontal dimension of the lateral force resisting system in any story is more than 150% of that in an adjacent story. The setback can also be visualised as a vertical re-entrant corner.

B. Characteristics Of Vertical Seismic Irregularities

In general, when an earthquake occurs, the first response of a building is not to move at all due to the inertia of the structure's mass. Almost instantaneously, however, the acceleration of the ground causes the building to move sideways at the base causing a lateral load on the building and a shear force at the base, as though forces were being applied in the opposite direction. The magnitude of seismic loading attracted to the building depends mostly on structure's mass and acceleration. However, the acceleration of the building depends on its natural period. Interestingly, the period, in turn, depends strongly on the structure's mass and stiffness and as the structure oscillate, the forces applied to it are transmitted through the structure to the foundation according to its mass and stiffness contribution. This was observed in a research of N.Kara[7] which documented that the variation of the load path depends on the stiffness distribution in the columns and beams. If a gap or discontinuity exist along lateral force resisting members, then transmission path is altered and then the internal forces will not be transferred effectively. This creates a weak point in the transmission path which induces a greater stress concentration, or plastic deformation problems. Members around the weak points get damaged and the resulting structure appears unstable and finally severe destruction is experienced by the structure. [19]. Also if the various upper stories exhibit a non-uniform stiffness and mass distribution, there is no smooth transfer of forces and residual stress is hence developed in the members. A serious problem occurs when soft story occurs on the ground floor because this is where the lateral loads are the greatest.

Appropriate measures that have taken by experts is to provide base isolation technique to isolate the structure from the potentially dangerous ground motions. It also provides an additional means of energy dissipation, thereby reducing the transmitted acceleration into the superstructure. This decoupling effect allows the building to behave more flexibly which improves its response to an earthquake. These isolators behave like rollers under the structure and keep the building a steady state even when the ground shakes. Thus no force is transferred to the building due to shaking of the ground. In the case of vertical Irregular structures, the time period is significantly increased when base isolation technique is used[14]. L. Di Sarno et al[15] conducted a comprehensive analysis of a structure using 327 high-damping rubber bearings and observed 70% reduction of maximum floor acceleration with respect to the ground acceleration. Also, the acceleration profile was uniform along the height of the multi-story frame structure. The principal characteristic of base-isolated structures is that most of the energy applied to the building is absorbed by the seismic isolation story, reducing the load on the upper structure[16]. To this end, it is convincing enough to implement isolation measures to a vertical irregular structure to effectively improve seismic performance.

IV. THE IMPACT OF VERTICAL CORRELATION ANALYSIS OF ISOLATED STRUCTURES IRREGULARITIES

Two actual isolated structures were used as a case study. Their modelling parameters are presented in Table I. Parameters been studied under this case study are mass, stiffness, shear force and damping coefficient.

TABLE I. SEISMIC PROPERTIES OF STUDY BUILDINGS

Parameter	Appearance	
	Building 1	Building 2
Plan Shape	Rectangle	Rectangle
No. of Story	7	7
Intensity	9 degrees	8 degrees
Acceleration(□□	0.40g	0.20g
Isolation layer	Base level	1st-floor level
Structural system	R.C Frame	R.C shear wall frame + slab

Two actual isolated structures were used as a case study. Building structure has a rectangular plan geometry with seven floors, where the upper structure is mainly frame reinforced concrete, which is based on the foundation pile. The earthquake intensity of the building was set to 9 degrees and acceleration (□) is designed to be substantially 0.40*g and* the design earthquake group is set to Group 1; Meanwhile, the second building structure has a rectangular plan shape [20] with the upper-structure bearing six stories and a base structure of one story. The upper structure uses a shear wall as the lateral force defense system. The structure is frame structure with floor slab system, which is based on an isolated foundation; intensity buildings designed to be 8 degrees, the basic design acceleration 0.20g.

In order to provide convenience to discussions, the story isolation system can be generally simplified to two-mass model to simulate the mechanical characteristics of these two models (Building 1 & Building2).

The structure system can be divided into an upper and a lower portion based on the isolation layer in the structure, wherein the upper substructure is treated as a single lump mass. In the scenario where the isolation is put at the roof level, the mass of the upper structure of the system will be small.

The lower sub-layer structure can be regarded as a single lump mass. Constraint conditions of this single-mass system, the lower sub-structure system stiffness and whole structural stiffness are the same. Also, the natural period is the same as the fundamental period of the original system. In general, the layer which exhibited a sudden change of the lump mass will not bring too much influence to the damping effect of the isolation structure, but the layer which showed a sudden change of the stiffness will adversely affect damping effect of isolation structure [21]. This is similar to the door into the kit, Shi Qingxuan in "irregular vertical reinforced concrete frame structures based on the seismic performance evaluation method" has a text view. While a newly mutated vibration layer the first layer, in which the damping effect will be under the best condition, as Stiffness layer, the intermediate layer is a cushioning effect of the worst layer.

In the isolated structure, if the upper structure has many layers, a higher height of the building, its structure is relatively flexible, when doing a seismic design, multiple lump mass model will be considered. Usually, the horizontal stiffness is comparatively smaller to the vertical stiffness of the isolation, therefore, during the implementation of dynamic analysis, the vertical displacement and deformation portion are ignored and hence analysis needs to be done only on the horizontal displacement and deformation behaviour.

Generally, isolated structures can be simplified as an interlaminar shear model, each floor is a basic unit, each of the floor slab can be considered as a lump mass, every story’s column can be considered as a vertical member, each member stiffness can be considered as equivalent shear stiffness. The increase of shear stiffness will make the isolation structure more efficient, which will have positive significance in ensuring the overall quality of construction.

V. CONCLUSION

With the continuous development of structures in seismic prone zones, the isolation technique is highly preferred during the construction. The vertical irregularities affect the isolation effect to a certain extent, for example, vertical mass distribution and stiffness irregularities of the isolated structure will reduce the isolation effect. Therefore, appropriate measures are extremely important to be taken during the construction to prevent vertical irregularity problems, and effectively improve the overall performance of seismic isolation building. In presence of isolator, there is a significant decrease in elastic-plastic displacement angle between the layers, but in the case of the layer with sudden change of mass and stiffness, or the adjacent layer, there may still be an interlayer displacement angle problem, consequently, during the part of the design, and hence it must be given high priority, to avoid any problems.

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