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Seismic vulnerability assessment of setback buildings using pushover analysis

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ABSTRACT:

Preliminary seismic risk assessment tools are used to screen existing buildings against potential seismic hazards. In most of the existing rapid or level 1 seismic risk assessment methods, buildings with vertical irregularities are usually assigned a constant score modifier which is higher than regular structures because of the complexity in the configuration that leads to a higher vulnerability. However, there are many types of vertical irregular structures and even for the same type such as buildings with setback, there are irregularity parameters that affect the seismic performance of these buildings.

This paper aims to refine the score modifiers for buildings with setback by introducing irregularity parameters. Using a horizontal and vertical dimension parameter, the severity of the setback is defined for the study. A static pushover analysis is utilized to determine the performance of the building under different irregularity conditions. The output of the study may be used to improve existing level 1 seismic risk assessments.

The study found that one of the primary concerns in the existence of vertical irregularities such as a setback is the localization of seismic demand. For setback buildings, the concentration of seismic demand is around the area joining the tower and base portion of the building. Data from the pushover analysis is translated into score modifiers for the varying setback severity.

1 INTRODUCTION

Earthquakes are considered to be one of the most unpredictable and devastating natural hazards. Earthquakes pose multiple hazards to a community, potentially inflicting large economic, property, and population loss. One of the measures used in order to combat or reduce the devastating effects of earthquakes is through the seismic risk assessment of existing buildings.

Several procedures have been developed in order to allow communities to prevent and mitigate losses in the event of an earthquake. One such technique is assessing existing buildings to determine which buildings are potentially safer if an earthquake is to occur. However, the amount of structures is too large and would take a significant amount of time and resources to be assessed in detail. A preliminary assessment is then introduced in order to determine which buildings should be prioritized for a detailed assessment. One such tool is the American tool FEMA154 by the Applied Technology Council and Federal Emergency Management Agency (ATC 2002). It should be emphasized that preliminary assessment procedures are merely tools for prioritization and cannot actually determine if a building is definitely safe from earthquakes.

The FEMA154 have become the model for a number of rapid visual screening tools of several countries. Canada, India, New Zealand, and several others, followed the framework of FEMA154, developing their own rapid visual screening tool for potential seismic hazards to suite local structural codes and conditions.

In preliminary seismic risk assessments, there are several parameters considered such as the soil type, seismic zoning, structural system, material type, height, irregularities, and etc. These assessment tools are widely used throughout different countries and accepted as an effective tool for risk assessment. Still, improvements to the assessment tool can still be introduced which allows it to be more refined. One such improvement that can be introduced is in the area of vertical irregularities. Vertical irregularities are basically building characteristics that demands for more complex design due to the different seismic demand experienced. This results to irregular buildings being more susceptible to earthquake damage as can be seen from several past earthquakes such as the 22 February 2011 Christchurch earthquake (Kam W. & et al. 2011). An example of a vertical irregularity are buildings with setbacks. This can be further broken down into the different types of irregularities as well as their severity for a more refined assessment tool.

1.1 Pushover Analysis

Pushover analysis is one of the methods available for evaluating buildings against earthquake loads. As the name suggests, a structure is induced incrementally with a lateral loading pattern until a target displacement is reached or until the structure reaches a limit state. The structure is subjected to the load until some structural members yield (Kadid A. & Boumrkik A. 2008). The model is then modified to account for the reduced stiffness of the building and is once again applied with a lateral load until additional members yield. A base shear vs. displacement capacity curve and a plastic hinging model is produced as the end product of the analysis which gives a general idea of the behavior of the building.

Although it is acknowledged that other types of analysis such as the dynamic time-history analysis is more accurate, the preliminary assessment nature of the objective would allow a simple static pushover analysis to be used (Merter O. and Ucar T. 2013). Several studies have also utilized this type of analysis in studying irregular buildings. (Ahamed S. & Kori J. 2013)

There are several documents available that provide guidelines when performing a nonlinear static analysis (static pushover analysis). These documents offer guidelines on things such as the computation of the target displacement, and things to consider for a proper analysis such as the modelling rules. The ATC-40 document by the Applied Technology Council is followed in this study (ATC 1996).

The building analyzed go through various performance levels which describes a limiting damage condition for a building. As the displacement of the building increases, so does the damage as illustrated in figure 1. The performance levels are commonly defined as follows,

- **Immediate Occupancy IO:** Damage is light and structure retains most of its original strength and stiffness. There may be minor cracking on the structural members.
- **Life Safety LS:** Substantial damage to the structure and the structure may have lost a large portion of its strength and stiffness.
- **Collapse Prevention CP:** Severe damage and little strength and stiffness remains. Building is unstable and is near collapse.

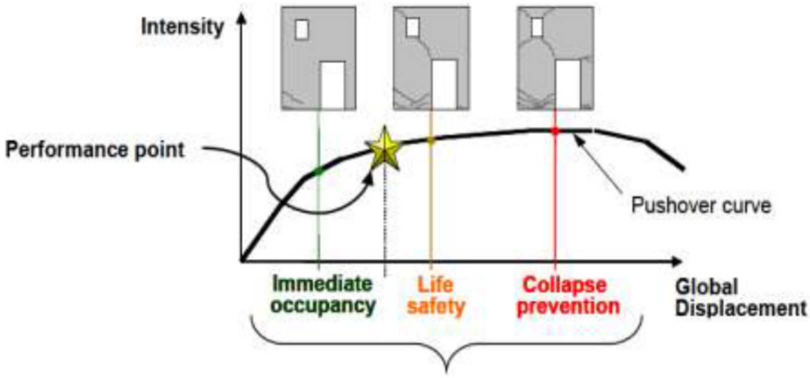


Figure 1 Performance Levels by Mouzzoun M. & Moustachi O (2013)

2 METHODOLOGY

A static pushover analysis using SAP2000 was utilized in the research. Due to the UBC97 based National Structural Code of the Philippines (NSCP) limitation in using this method of analysis, only a low-rise 5 story building was modelled (ASEP 2003). A concrete frame building with 3 bays at 6 meters each is modelled. The number of bays vary in actual buildings but based on a survey of over 100 random low story buildings around Manila, Philippines, 3 bay concrete buildings are the most common. A story height of 3 meters is kept constant throughout each story and model except when the irregularity is introduced.

The model is also constructed considering code provisions as well as guidelines given by the ATC-40 document. Section sizes are determined so that it will be able to accommodate every type of model. The model is made so that the fundamental period of vibration of the building does not exceed 1.0s to ensure the first mode of vibration dominates. Other limits such as the maximum inter-story drift limit of 2.0% is also observed. Figure 2 shows the geometry of the regular building model considered.

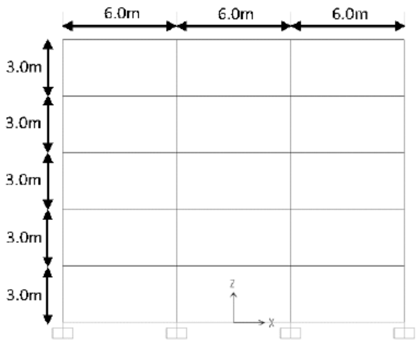
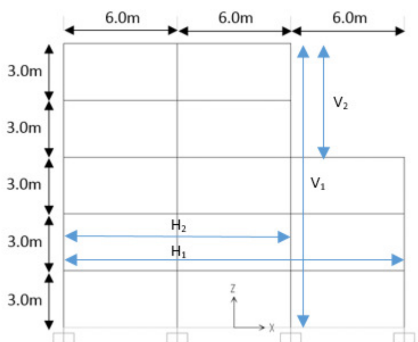


Figure 2 Regular Building

Default SAP2000 hinges are used in the analysis. M3 hinges are assigned on beam ends and P M2 M3 hinges are assigned on column ends as per ATC-40 recommendations. A triangular codal type of loading is consider in the analysis wherein the loading on a story is a function of its mass and height from the ground. The model is pushed to a target displacement determined automatically by SAP2000 using ATC-40 recommendations. This target displacement is the displacement experienced by the building given the design earthquake.

There are numerous possible configurations of setbacks in a building. However, this study will only be limited to one step setback since this is the most common case. The first parameter is the ratio of two adjacent stories. As defined by the NSCP, a setback with more than 130 percent (or a ratio of 1.3) of an adjacent story is considered vertically irregular. This will be referred to as the horizontal setback ratio (H_R) of a building. Another parameter to vary is the height of the setback. This will be referred to as the vertical setback ratio (V_R). A five story building for instance, with a two stories setback will have a vertical setback ratio of 1.67. An illustration can be seen in figure 3.



$$H_R = \frac{H_1}{H_2} = \frac{18m}{12m} = 1.5$$

$$V_R = \frac{V_1}{V_2} = \frac{15m}{9m} = 1.67$$

Figure 3 Setback Irregularity Model

In order to prevent a discontinuity of lateral force systems to occur, the decrease in horizontal dimension should end with a full column. Since the configuration of the building limits the H_R to between 1.5 and 3.0, modifications are done to determine the performance of the building with other setback ratios. From a survey of over 30 buildings around a local area with setbacks, common horizontal setback ratios range from 1.3 to 4.0. The first and/or second bays are increased or decreased in length in order to accommodate the other horizontal setback ratios. A new regular building model is created for every adjustment of span length for proper comparison as seen in figure 4.

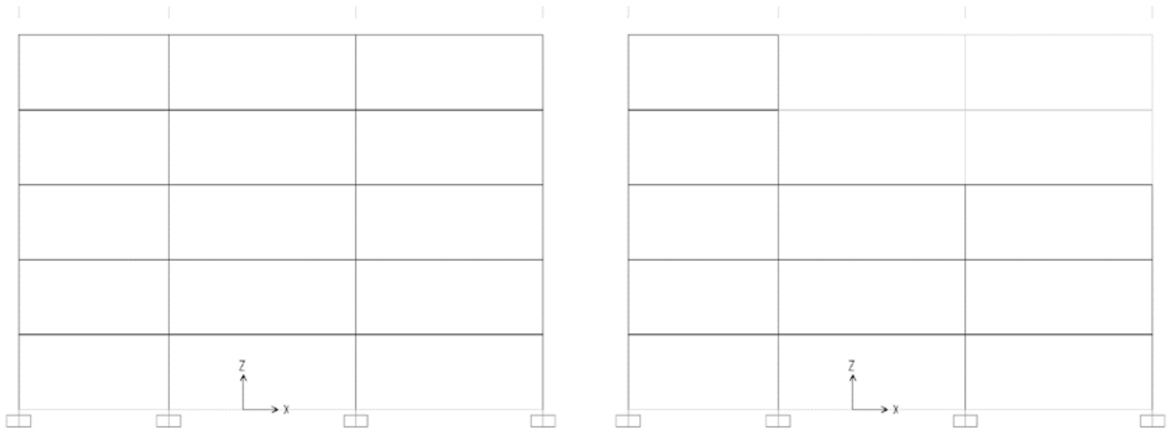


Figure 4 Modified Regular Building and Irregular Building

3 RESULTS AND DISCUSSIONS

The plastic hinge formation as well as the seismic design of the building is shown in the paper. The data gathered are some of the important seismic indicators in analyzing buildings. All data are gathered using SAP2000.

3.1 Plastic Hinge Formation

Plastic hinge formation is one of the primary data analyzed by researchers to identify location of the building where larger potential damage may occur. Assigned plastic hinges reach a specific hinge rotation limit and go through different damage states. ATC-40 recommends limit states but default SAP2000 hinge limits are adopted in the study. Figure 4 shows the SAP2000 color legend indicating the increasing damage severity of the hinges.

Figure 5 Hinge Severity Legend

Figure 5 shows the hinge formation of the regular (a) and irregular building with an H_R and V_R of 3.0 and 5.0 respectively (b). For irregular buildings, formation of hinges more localized in an area compared to the more evenly distributed hinge formation for the regular buildings. For irregular buildings, formation and yielding progression of the majority of hinges start on the segment of the building without the setback and on the upper floors of that segment. For the regular buildings on the other hand, hinge progression start on the center of the structure. This could indicate a more evenly distributed damage. It can be seen that a concentration of the severity of the hinges is present on the tower portion of the building.

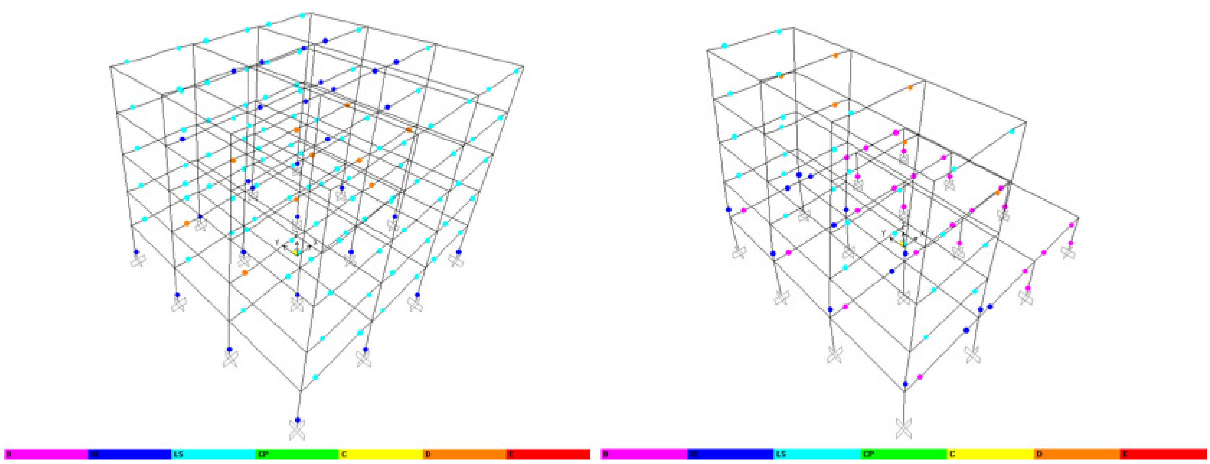


Figure 6 (a) Regular Building Hinge Formation (b) Setback Building Hinge Formation.

3.2 **Seismic Design**

Figure 7 shows the area of reinforcements needed (in square meter) for the building to be up to code standards. Taking a look at the amount of reinforcement required for the irregular buildings, it can be observed that there is a significant demand in the inner column at the bottom of the tower portion of the building relative to the other columns of the building. This might indicate that this is where the critical area of the building is where local collapse is most likely to occur. The bottom right outer and inner columns of the irregular building also had a bigger demand than the bottom left outer and inner columns. These differences in design for the left and right segment of the building shows the considerable asymmetry of the demand in the irregular building.

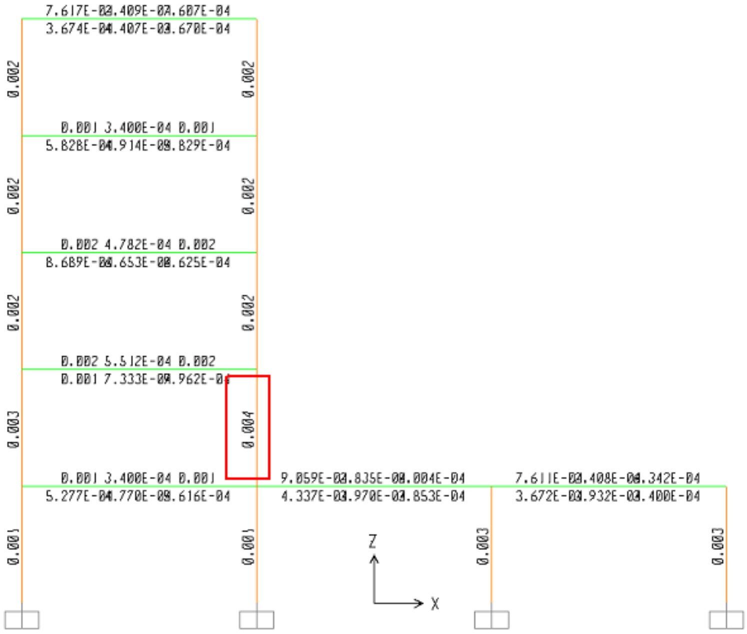


Figure 7 Seismic Design Of Setback Building

3.3 **Vulnerability Index**

From the detailed analysis of the different types and configurations of irregularities, it has been observed that the primary cause for concern regarding the risk of irregular buildings lie under the increased risk due to local failure. Localization of seismic demand (local hazard) was observed in the buildings. The building vulnerability index original proposed by Lakshmanan (2006) is modified in an attempt to produce a local vulnerability index for the frames of each story. As stated on a previous section, the modified equation is as follows,

$$VI_{Loc_i} = \frac{\left[1.5 \sum N_j^c x_j + \sum N_j^h x_j\right]_i}{\left[\sum N_j^c + \sum N_j^h\right]_i} \tag{1}$$

Here, N_j^c and N_j^h are the number of hinges in columns and beams respectively, for the jth performance range. The summation sign is intended to cover the performance ranges, j = 1,2…6. The *i* indicates the story frames inconsideration.

Table 1. Vulnerability index weightage factors.

Serial Number	Performance Range (*j*)	Weightage Factor (x_j)
1	< B	0
2	B-IO	0.125
3	IO-LS	0.375
4	LS-CP	0.625
5	CP-C	0.875
6	C-D, D-E, and > E	1.000

The vulnerability index approach was chosen instead of simply checking the individual seismic demand forces such as the moment and shear because it is less tedious. Checking for each beam and column of the building would be rather time consuming. Furthermore, simply checking the states of the plastic hinges allows any interaction among the structural members to be taken into account. ATC-40 hinge recommendations are followed.

The score modifier of each irregular building model comes down to the difference in distribution of the local vulnerability index relative to the regular building considered. The local vulnerability index of each frame of the building considered is determined using equation 1 and the distribution of the local vulnerability relative to the entire building vulnerability is determined. The distribution of the local vulnerability is determined using the equation,

$$VI_{D_i} = \frac{VI_{Loc_i}}{Total\, VI_{Loc}} \times 100 \tag{2}$$

Wherein VI_{D_i} is the distribution of the local vulnerability index at frame *i* and VI_{Loc_i} is the local vulnerability index at frame *i*. The increase in the vulnerability index distribution can simply be computed as,

$$VI_{F_i} = \frac{VI_{D_i} of\ Irregular\ Building\ Frame}{VI_{D_i} of\ Regular\ Building\ Frame} \tag{3}$$

Wherein VI_{F_i} is the vulnerability index factor that shows the increase in VI_{D_i} for frame *i*. The largest VI_{F_i} is then defined as the score modifier for the irregularity configuration.

The results of determining the local vulnerability index of the regular building can be seen in table 2. The damage throughout the building is more or less evenly distributed with the exception of the first story frames. The first story frames had a larger VI_{Loc} only due to the hinges that developed on the columns.

Table 2. Regular building hinge count.

Regular Building	To tal	Columns				Beams				VI
		B-IO	IO-LS	LS-CP	D-E	B-IO	IO-LS	LS-CP	D-E	
1st Frame	80	8	8	0	0	0	24	0	0	0.1875
2nd Frame	80	0	0	0	0	0	24	0	0	0.1125
3rd Frame	80	0	0	0	0	0	24	0	0	0.1125
4th Frame	80	0	0	0	0	0	24	0	0	0.1125
5th Frame	80	0	0	0	0	0	24	0	0	0.1125

Table 3 shows the local vulnerability indices of the setback irregularity case with an H_R and V_R of 1.5 and 2.5 respectively. It is rather unclear where the localization of plastic hinges occur when just the local vulnerability indices are checked directly. There is minimal difference between the regular and irregular building when checked directly. Frames above the dotted line are story frames that belong to the base portion of the structure, and frames below the dotted line belong to the tower portion of the structure. A summary of some setback cases can be seen in table 4.

Table 3. Irregular building hinge count.

1.5_2.5	To tal	Columns				Beams				VI
		B-IO	IO-LS	LS-CP	D-E	B-IO	IO-LS	LS-CP	D-E	
1st Frame	80	16	0	0	0	0	24	0	0	0.15
2nd Frame	80	0	0	0	0	0	24	0	0	0.1125
3rd Frame	58	0	0	0	0	0	16	0	0	0.1034
4th Frame	58	0	0	0	0	0	16	0	0	0.1034
5th Frame	58	0	0	0	0	0	16	0	0	0.1034

Table 4. Setback building local vulnerability indices.

	Local Vulnerability Index								
Loc/Case	**Reg.**	**1.5_1.3**	**1.5_1.7**	**1.5_2.5**	**1.5_5.0**	**3.0_1.3**	**3.0_1.7**	**3.0_2.5**	**3.0_5.0**
1st Frame	0.1875	0.1969	0.1500	0.1500	0.1234	0.2063	0.1500	0.1219	0.0484
2nd Frame	0.1125	0.1125	0.1125	0.1125	0.1034	0.1125	0.1125	0.1063	0.0833
3rd Frame	0.1125	0.1125	0.1125	0.1034	0.1034	0.1125	0.1125	0.0833	0.0833
4th Frame	0.1125	0.1125	0.1034	0.1034	0.1034	0.1125	0.0833	0.0833	0.0833
5th Frame	0.1125	0.1034	0.1034	0.1034	0.1034	0.0833	0.0833	0.0833	0.0833
Total	0.6375	0.6378	0.5819	0.5728	0.5372	0.6271	0.5417	0.4781	0.3818

The table below (table 5) shows the distribution of the local vulnerability indices determined through equation 2. In most cases, when the V_R is kept constant, increasing the H_R resulted in a larger increase in one of the VI_D relative to its respective regular building. The same can be said when the H_R is held constant and the V_R is varied. This shows that there is a concentration of vulnerability along the building. This observation is clearer when the VI_F is determined.

Table 5. Setback building local vulnerability distribution.

	Vulnerability Index Distribution								
Loc/Case	**Reg.**	**1.5_1.3**	**1.5_1.7**	**1.5_2.5**	**1.5_5.0**	**3.0_1.3**	**3.0_1.7**	**3.0_2.5**	**3.0_5.0**
1st Frame	29.41	30.87	25.78	26.19	22.98	32.89	27.69	25.49	12.69
2nd Frame	17.65	17.64	19.33	19.64	19.26	17.94	20.77	22.22	21.83
3rd Frame	17.65	17.64	19.33	18.06	19.26	17.94	20.77	17.43	21.83
4th Frame	17.65	17.64	17.78	18.06	19.26	17.94	15.38	17.43	21.83
5th Frame	17.65	16.22	17.78	18.06	19.26	13.29	15.38	17.43	21.83

Table 6 shows the increase in VI_D of the irregular building to the regular building determined through equation 3. In the case of setback buildings, the vulnerability of most of the models is along the location of the setback. It is unclear if the local vulnerability concentration is on the top frame of the base section of the structure or on the bottom frame of the tower portion of the setback building. Regardless, it is observed that the sudden change in stiffness, strength, and mass of the building is the location of the local vulnerability

Table 6. Setback building local vulnerability factor.

	Vulnerability Index Factor								
Loc/Case	**Reg.**	**1.5_1.3**	**1.5_1.7**	**1.5_2.5**	**1.5_5.0**	**3.0_1.3**	**3.0_1.7**	**3.0_2.5**	**3.0_5.0**
1st Frame	1.00	1.05	0.88	0.89	0.78	1.12	0.94	0.87	0.43
2nd Frame	1.00	1.00	1.10	1.11	1.09	1.02	1.18	1.26	1.24
3rd Frame	1.00	1.00	1.10	1.02	1.09	1.02	1.18	0.99	1.24
4th Frame	1.00	1.00	1.01	1.02	1.09	1.02	0.87	0.99	1.24
5th Frame	1.00	0.92	1.01	1.02	1.09	0.75	0.87	0.99	1.24

Table 7 is the proposed score modifiers which is simply based on the VI_F shown in table 6. The varying H_R and V_R is divided into three ranges which may also be categorized as low, medium, and high risk. Do note that other tables showing the vulnerability index distribution and factors of other setback configurations is not shown due to content limitations.

Table 7. Proposed setback irregularity score modifiers.

Proposed Score Modifiers			
H_R/V_R	**1.2 – 1.6**	**1.7 – 2.5**	**2.6 – 5.0**
1.3 – 2.0	1.10	1.10	1.10
2.1 – 2.5	1.10	1.30	1.30
2.6 – 4.0	1.20	1.50	1.60

The irregularity modifiers can be used to adjust rapid visual screening (RVS) scores such as the FEMA 154 and those developed by Brizuela and Oreta (2013) which uses the definition of Risk = Hazard x Asset x Vulnerability. The Vulnerability for irregular structures can be adjusted as Vulnerability x Modifier. Given an irregular setback building whose H_R and V_R values are 2.8 and 2.0 respectively, the modifier is determined as 1.50 and this value will be multiplied to the current vulnerability.

4 CONCLUSION

Upon analysis of the modelling results for the setback building, it can be seen that the main cause for setback buildings to be more susceptible to earthquakes is the localization of seismic forces. Though the total demand on the building is smaller due to the lesser overall mass, uneven demands on the areas of the building results to a local hazard. The forces are concentrated on the segment of the building where there is a reduction in stiffness which is at the top of the base and/or the bottom of the tower portion. This can be observed through the development of the plastic hinges, the story drift of the buildings, as well as the design. These seismic parameters show a localization of seismic demand. The risk of the building is increased due to the increased hazards of specific areas of the building. The increase in risk is also dependent on the amount or the severity of setback of the building and thus the both horizontal and vertical setback ratios is further categorized to consider its severity. These irregularity modifiers may serve as calibrated vulnerability model modifiers for seismic risk assessment. It is recognized that any building that is designed properly will be able to withstand seismic excitation without incurring considerable damage.

REFERENCES:

Ahamed S. & Kori J. 2013. Performance based seismic analysis of an unsymmetrical building using pushover analysis. *International Journal of Engineering Research*. Vol 1 (2), 100-110.

Association of Structural Engineers of the Philippines. 2003. ASEP earthquake design manual, Quezon City: ASEP, Inc.

ATC. 1996. Seismic evaluation and retrofit of concrete buildings (ATC-40). *Seismic Safety Commission, California*.

ATC. 2002, Rapid visual screening of buildings for potential seismic hazards: A handbook. 2nd Edition. *FEMA 154, Redwood, California: Applied Technology Council.*

Brizuela K. & Oreta A. 2013. Computer-aided seismic hazard risk assessment tool to promote safe school communities. *De La Salle University – Manila*. Philippines.

Kadid A. & Boumrkik A. 2008. Pushover analysis of reinforced concrete frame structures. *Asian Journal of Civil Engineering*, Vol 9 (1), 75-83.

Lakshmanan N. 2006. Seismic evaluation and retrofitting of buildings and structures. *ISET Journal of Earthquake Technology*. Vol. 43 (1-2), 31-48.

Kam W., Pampanin S. & Elwood K. 2011. Seismic performance of reinforced concrete buildings in the 22 February Christchurch (Lyttelton) earthquake. *Bulletin of the New Zealand Society for Earthquake Engineering*. Vol. 44 (4), 239-278.

Merter O. & Ucar T. 2013. A comparative study on nonlinear static and dynamic analysis of RC frame structures. *Journal of Civil Engineering and Science*. Vol 2 (3), 155-162.

Mouzzoun M. & Moustachi O. 2013. Seismic performance assessment of reinforced concrete buildings using pushover analysis. *ISOR Journal of Mechanical and Civil Engineering*, Vol 5 (1). 44-49.