Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 124

STRUCTURAL IRREGULARITIES AND THE BUILDING CODES

B. Baradaran-Seyed[1]

ABSTRACT

In this abstract, structural irregularities as defined in UBC, ASCE 7, and NBC, with more emphasis on the latter, and their impact on the design of high-rise buildings shall be discussed. Structural irregularities as defined in the code aim to restrict the engineers from designing structures with complicated behavior or conduct them toward using more advanced analysis techniques.

In this document some examples are provided and the challenges that practicing engineers face are discussed.

Introduction

Structural Irregularities were introduced in the codes in the 80s and since then have evolved continuously. UBC 97 is extensively used in Middle East, while use of ASCE 7 and NBC is generally restricted to USA and Canada respectively. While all these codes follow the same concepts, there are major differences in the new version of NBC compared to UBC 97 and ASCE 7. For practicing engineers who frequently use these codes, these differences cause many challenges. Irregularities indeed were introduced to draw a line between different analysis methods and in some cases prevent the designer from having them in the structures.

Definitions of Vertical Stiffness and Torsional Sensitivity Irregularitis in NBC are different from the other codes. For post–disaster building with seismic hazard index of greater than 0.35 these types of irregularities should be avoided. Several questions arise in this regard: Why dynamic analysis does not cover the real behavior of these buildings? What are the impacts of these code requirements on the day to day design of practicing engineers? Are there any recommendations and solutions to go around these requirements?

[1] Senior Project Manager, Halsall Associates LTD. 2300 Yonge Street, Suite 2300, Box 2385, Toronto, Canada M4P 1E4

Uniform building Code

Structural irregularities were introduced in UBC in 1988 and stayed intact in the last edition of 1997. UBC categorizes the irregularities to plan and vertical structural types as shown in the Tables 1.a & 1b.

Table 1.a Vertical Structural Irregularities

Irregularity Type and Definition
1. **Stiffness irregularity—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
2. **Weight (mass) irregularity** Mass irregularity shall be considered to exist where the effective mass of any story is more than 150 percent of the effective mass of an adjacent story. A roof that is lighter than the floor below need not be considered.
3. **Vertical geometric irregularity** Vertical geometric irregularity shall be considered to exist where the horizontal dimension of the lateral force-resisting system in any story is more than 130 percent of that in an adjacent story. One-story penthouses need not be considered.
4. **In-plane discontinuity in vertical lateral-force-resisting element** An in-plane offset of the lateral-load-resisting elements greater than the length of those elements
5. **Discontinuity in capacity—weak story** A weak story is one in which the story 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.

For structures with vertical structural irregularities type 1, 2, and 3, dynamic analysis procedure should be used. For types 4 and 5 irregularities, surprisingly dynamic analysis procedure is not required; the structural elements supporting such discontinuous systems shall have the design strength to resist the maximum force that can be transferred to them by the lateral-force-resisting system for type 4 and Ωo times the design force prescribed by this code for type 5. Ωo is defined as the seismic force amplification factor accounting for structural overstrength.

Table 1.b Plan Structural Irregularities

Irregularity Type and Definition
1. **Torsional irregularity—to be considered when diaphragms are not flexible** Torsional irregularity shall be considered to exist when the maximum story drift, computed including accidental torsion, at one end of the structure transverse to an axis is more than 1.2 times the average of the story drifts of the two ends of the structure
2. **Re-entrant corners** Plan configurations of a structure and its lateral-force-resisting system contain re-entrant corners, where both projections of the structure beyond a re-entrant corner are greater than 15 percent of the plan dimension of the structure in the given direction.
3. **Diaphragm discontinuity** Diaphragms with abrupt discontinuities or variations in stiffness, including those having cutout or open areas greater than 50 percent of the gross enclosed area of the diaphragm, or changes in effective diaphragm stiffness of more than 50 percent from one story to the next.
4. **Out-of-plane offsets** Discontinuities in a lateral force path, such as out-of-plane offsets of the vertical elements.
5. **Nonparallel systems** The vertical lateral-load-resisting elements are not parallel to or symmetric about the major orthogonal axes of the lateral-force-resisting system.

Re-entrant Corner Irregularity seems to be redundant, as the result of any reentrant corner will be reflected in weight and/or torsional irregularity. Figure.1 is an example of a plan with reentrant corner which by providing a well designed lateral system, would demonstrate regular behavior.

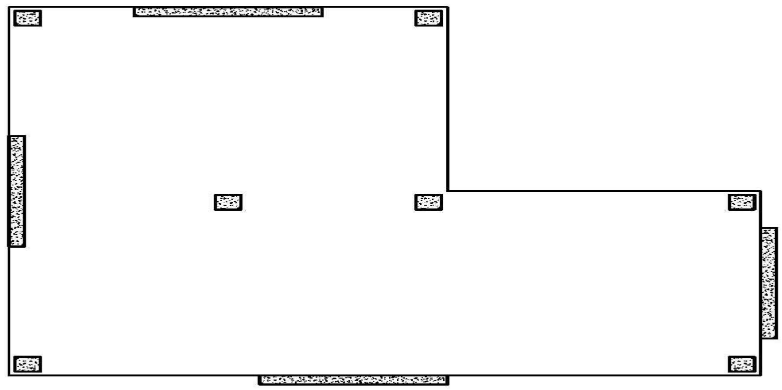


Figure.1 Plan with reentrant corner and structurally regular behavior

ASCE 7

ASCE 7 uses the same structural irregularity definitions as UBC with the exception that it has sub-classification for extreme torsional irregularity where maximum computed story drift, including inherent plus accidental torsional moment, at one end of the structure transverse to an axis is more than 1.4 time the average of the story drifts at the two ends of the structure along the axis being considered. As per UBC and ASCE 7, the accidental torsional moment is caused by assumed displacement of the center of mass each way from its actual location by a distance equal to 5 percent of the dimension of the structure perpendicular to the direction of the applied forces. These requirements have been repeated in all later versions of ASCE 7.

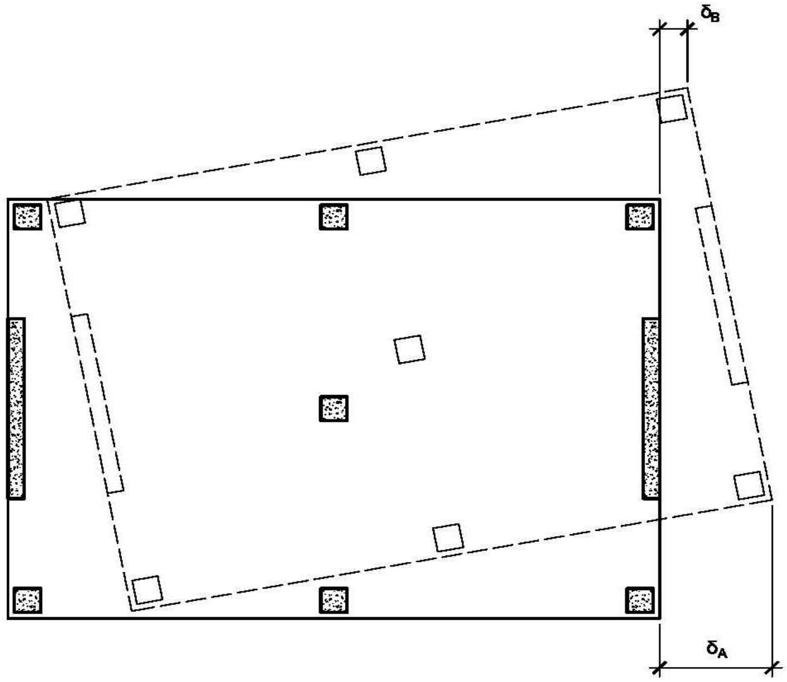
It also has extreme soft story classification in which the lateral stiffness is less than 60% of that in the story above or less than 70% of the average stiffness of the three stories above.

Except for seismic design category A, for other categories (B, C, D and E) dynamic analysis procedure is prescribed; the forces in structural elements transferring the loads arising from such irregularities to other elements, shall be increased from 25% up to 300% depending on the seismic design category.

Also, Section 12.8.4.3 requires a torsional moment amplification factor of

$$A_x = [\delta_{max}/(1.2\ \delta_{ave})]^2 \leq 3$$

To be applied to the accidental torsional moment.



$\delta_{ave} = (\delta_A + \delta_B)/2$ & $\delta_{max} = \max(\delta_A \;\&\; \delta_B)$

Torsional irregularity exists if $\delta_{max} \geq 1.2\delta_{Ave}$
Extreme Torsional irregularity exists if $\delta_{max} \geq 1.4\delta_{Ave}$

Figure.2- Torsional irregularity and amplification factor A_x

For seismic design category E and F, structures with extreme torsional and extreme soft story irregularities shall not be permitted as per section 12.3.3.1.

The above noted sections of the ASCE 7 seem to contradict each other. As in one of them there is a requirement for torsional amplification while in the other for the same seismic design category the extreme torsional irregularity is prohibited. To eliminate the confusion, the following revision to the section 12.8.4.3 would be appropriate (underlined italic words are by the author):

" 12.8.4.3 Amplification of Accidental Torsional Moment. Structures assigned to Seismic Design Category C, D, E, or F, where type 1a 0r 1b torsional irregularity exists as defined in Table 12.3-1 *and not prohibited as per Section 12.3.3.1* shall have the effects accounted for …."

There are other issues associated with the definition of torsional irregularity which will be discussed with NBC 2005 requirements.

International Building Code, IBC

For structural irregularities, IBC refers the user to ASCE 7 without any comments and modifications**.**

National Building Code of Canada, NBC

There was no coverage of irregularities in the different versions of the NBC until its latest version of 2005. NBC 2005 uses the same definitions as UBS with some exceptions as follows:

Reentrant Corners Irregularities,

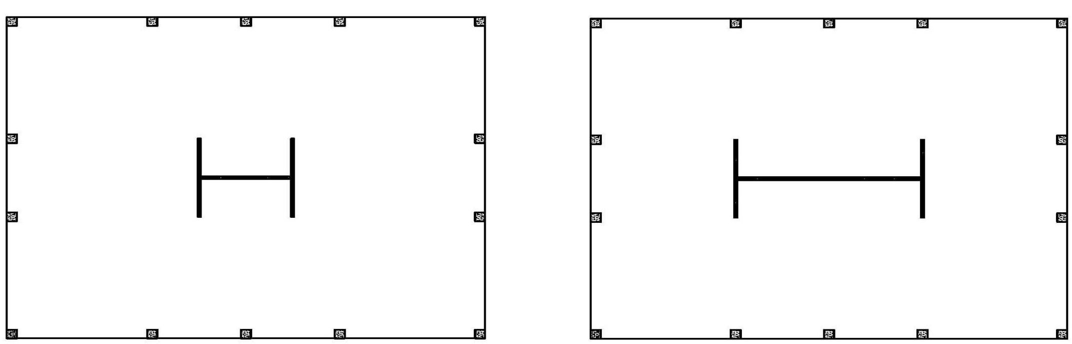
NBC has eliminated the reentrant corners irregularity from the list.

The Torsional Sensitivity

$B_x = \delta_{max} / \delta_{ave}$

Has been introduced. δ_{max} and δ_{ave} have the same definitions as shown on Figure.1 with the exception that they are obtained by applying a 10 percent accidental torsional moment.
As per NBC 2005, if B_x is larger than 1.7 then the structure is torsionally sensitive and irregular. For torsionally irregular buildings a 10 percent accidental torsional moment shall be considered compared with the 5 percent for other buildings. This is equivalent to an amplification factor of 2. The results of the dynamic analysis will be linearly added to the 10 percent accidental torsional effects obtained from the static analysis.

For post-disaster building Torsional Irregularity is not permitted. Figure.2 shows a typical plan of a post- disaster building.



a- with short core b- with long core

Figure.3- Building Plan with two core options

With the plan of Figure.3a, short core, the torsional sensitivity is less than 1.7. With

Figure.3b plan, the lateral stiffness is more than quadrupled while the torsional stiffness is almost doubled. The result is that the lateral deformations has substantially reduced and weight of the torsional deformations has increased with respect to the lateral deformation; As a result, plan of Figure.2b is torsionally sensitive and not permitted.

Results of the elastic time history analysis of these two buildings, subject to Elcentro Earthquake along the web of H core, are tabulated below. As Shown, the maximum B_x and the maximum inter-storey drift ratio at the upper most levels don't happen simultaneously. Surprisingly for the building of Figure.3b which is classified as irregular as per NBC 2005, the resulted Maximum Bx and Inter-story drift ratios are smaller than that of the regular one, Figure.3a. The results for both buildings have been obtained from the equal base shears.

Table 2- Results of time history analysis, Elcentro Earthquake

Building							
Figure.3a				Figure.3b			
Max B_x	Inter story Drift ratio	B_x	Maximum Inter storey drift ratio	Max B_x	Inter story Drift ratio	B_x	Maximum Inter storey drift ratio
232	1/1137	9.74	1/29	58	1/2000	1.2	1/1250

It is clear that with the increased capacity of the core of Figure 3.b, the "capacity design" procedure should be used. This means that the core should be designed for the loads as high as R_oR_d times the design earthquake loads. R_o and R_d are the system ductility and over strength related modification factors respectively as per NBC 2005. Flanges of the H shape core, representing the torsional resistance of the system, should be designed for the torsional moments magnified by a factor as high as R_oR_d. Other than this is, is this building really torsionally sensitive? Shouldn't the Code consider other parameters like torsion induced inter story drift ratios and/or absolute values of the torsion induced lateral deformations? While the rotation of the plan with respect to its at rest position looks critical, indeed it is the relative drift of the adjacent floors which creates the forces in the elements and not the floor torsional rotation by itself.

Vertical Stiffness Irregularity

NBC 2005 definition of vertical stiffness irregularity is similar to UBC with the exception that it includes levels below to the equations as follows (bold words represent the changes):

" Vertical Stiffness Irregularity shall be considered to exist when the lateral stiffness of the SFRS in a story is less than 70% of the stiffness of any ***adjacent*** storey, or less than 80% of the average stiffness of the three storeys above or ***below***"

This is a big change after having the definition of this type of irregularity intact in the codes for 17 years. In explanation of this definitions, (Users Guide – NBC 2005) refers the reader to (DeVall 2003) where it is indicated that the definition of the structural irregularities correspond closely to the definitions in the IBC and the UBC. There is no indication why such a big change has happened.

While both UBC and ASCE 7 permit vertical irregularities not to be applied where no story drift ratio under design lateral seismic force is greater than 130 percent of the story drift ratio of the next story above, NBC 2005 not only doesn't consider this relief, but surprisingly extend the criteria to levels below as well.

For Post-disaster buildings where the seismic hazard index is equal to or greater than 0.35 , this type of irregularity is not permitted; this means that basement levels with concrete basement walls are not allowed as the stiffness of these levels will definitely be more than 80 percent of the ground level. Does this mean that we should structurally isolate the basement walls and make them structurally self supported or simply don't have any basement levels. How practical are these solutions?

Another solution is to prop the building at the grade level, solve the super structure, and apply the reactions to the sub structure. This method has been used by many engineers during the last two decades for different reasons. The origin of this method is probably from Section1629.8.3 of UBC 1997 which permits the upper flexible part of the structure be separated from the lower rigid portion and analyzed with static method provided the lateral stiffness of the lower portion is at least 10 times that of the upper portion and period of the entire structure is not greater than 1.1 times the period of the upper portion considered as a separate structure fixed at the base. This method indeed moves us away from the dynamic analysis approach which is intent of the code.

Conclusions

The structural irregularities have been introduced to the building codes to: (a) to encourage engineers to select structural systems without any significant physical plan or vertical discontinuities, (b) to require dynamic analysis method be followed in case any type of irregularity exists, (c) to prohibit some types of irregularities in higher seismic zones or in buildings with higher importance category, (d) to impose penalties by increasing the design loads of the structural components in the vicinity of the discontinuities.

Definitions of some of the structural irregularities seem need modifications; more detailed criteria are required. For torsional irregularity some additional parameters like torsion only induced inter-story drifts and/or the inter-storey drift ratios resulted from the time history dynamic analysis may be required to be checked against the special code recommended values. It may also be required to design the structures so that there is significant separation between their torsional and translational periods of vibration; this will eliminate any possible amplification of earthquake induced displacements.

Definition of vertical stiffness irregularity in NBC 2005 is very controversial; it practically prohibits having basement levels in post-disaster buildings. It also does not permit post-disaster buildings to have higher than certain amount of lateral stiffness in any level compared to the level above. This condition not only doesn't excite the higher modes of vibration during the earthquake, but in fact increases the participation weight of the first mode which is a preferred condition. In the author's opinion, this definition deserves a special attention from the code committee and possibly deletion from the NBC.

Some of the irregularity types have been defined as discretized two dimensional types. With the extensive use of three dimensional modelers in the analysis of the structures, it deems necessary to modify these definitions to rely on overall three dimensional behaviors rather than the discretized two dimensional definitions.

References

ASCE Standard, ASCE 7-98, 1998. *Minimum Design Loads for Buildings and Other Structures, Chapter 9, Earthquake Requirements.*

ASCE Standard, ASCE 7-05, 2005. *Chapter 12, Seismic Design Requirements for Building Structures.*

International Building Code, 2009, ICC Publications

Ronald H. DeVall, 2003. *Background information for some of the proposed earthquake design provisions for the 2005 edition of the National Building Code of Canada,* Canadian Journal of Civil Engineering (30), 279-286

Uniform Building Code, International Code Council, 1988. *Part V Engineering Regulations, Chapter 23, General Design Requirements*

Uniform Building Code, International Code Council, 1997. *Volume 2, Chapter 16, Structural Design Requirements*,

User's Guide – NBC 2005, Structural commentaries (Part 4 of Division B), *Commentary J, Design for Seismic Effects.*

International Building Code, 200