Definition of Structural Irregularity in Seismic Codes

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The Issue

Aesthetic and architectural considerations often call for irregular structures with discontinuity in mass, stiffness, strength, geometry or structural form. Past earthquakes have shown that buildings with irregular configuration or asymmetrical distribution of structural properties trigger an increase in seismic demand, causing greater damage. Therefore, seismic codes provide elaborate empirical rules for the classification of buildings into regular, and various irregular categories as a function of asymmetries, to evaluate seismic demand. The codes have become increasingly cumbersome, with a plethora of experiential rules to account for irregularities from a multitude of structural asymmetries observed in the real world. There is a need to define and measure structural irregularity in a rational manner to assess its relative significance in different structures, and to develop seismic codes on a sound theoretical foundation. The major issue is the identification of a measurement scale for irregularity levels produced by asymmetric structural properties. This scale can then be used to specify quantifiable limits that delineate regular and different irregular building categories.

Regularity and Irregularity in Seismic Codes

Initially, the concept of structural irregularity was introduced in the Uniform Building Code (UBC) in a qualitative manner and potential irregularity markers were identified. Further evolution of seismic codes has refined this process and, starting in 1998, the UBC quantified the configuration parameters for building classification and stipulated specific analytical requirements for irregular structures. The distinction between regular and irregular structures was based on certain limiting ratios of strength, mass, setbacks or offsets of one story with respect to an adjacent story. For example, per the 2003 NEHRP *Recommended Provisions for New Buildings and Other Structures*, a building is defined to be vertically irregular by comparing the ratio of mass, strength or stiffness between adjacent stories using prescribed values, such as 70-80% for soft story, 80% for weak story and 150% for set-back structures. These limits follow from analytical and experimental studies, empirical observations or engineering judgment. Even though the limits are only applicable to building structures, it is not practical to cover exhaustively all the diverse irregularities that may arise in practice. There is also no guarantee that the specified limits are reasonable because the code stipulations are based on past observations which may result from a combination of discontinuities, and few studies are available to evaluate their independent impact. For example, vertical geometrical irregularity due to setbacks also will result in irregularities due to non-uniform distribution of mass and stiffness.

The current classification system for regular buildings, based on comparing the characteristics of adjacent stories, *implicitly* ensures that the mass or stiffness dissimilarity between stories is within reasonable limits to prevent ill-conditioning of relevant matrices in the structural model. Instead, based on the premise that asymmetric structural properties generate ill-conditioned matrices, it is possible to utilize a matrix condition number for *explicitly* defining the degree of irregularity via a non-dimensional metric ranging from 0 to 1.

Irregularity due to Asymmetric Structural Properties

The performance-based scale for irregularity measurement should be a function of the conditioning of the relevant matrices for mass or stiffness, represented in a generalized form by (n x n) matrix **X**. An irregularity makes the matrix **X** ill-conditioned, signified by its condition number k(**X**), which is defined using either matrix norms or eigenvalues. The larger the condition number, the closer is matrix **X** to singularity, which represents structural collapse. James Demmel showed in a 1987 paper, "On condition numbers and the distance to the nearest ill-posed problem" (*Numerische Mathematik*, Vol. 51, No. 3, pp 251-289), that the distance R to singularity is given by the reciprocal of the condition number. Consequently, the degree of irregularity IR can be defined as (1- R), where IR conveniently ranges between 0 and 1 with a higher value indicating a more irregular structure. This IR metric is calculated from the input data and provides a measure of irregularity for an individual discontinuity (e.g., mass) or multiple discontinuities (e.g., stiffness) through knowledge of the closeness of the matrix to singularity. Note that computation using the stiffness matrix provides the combined irregularity from multiple discontinuities, since this matrix integrates information about configuration, member sizes, material properties, connection types, and applied loads.

Structural System Irregularity

Seismic codes distinguish between irregularity levels triggered by asymmetric structural properties for the plan and vertical configurations, but there is no definition for the degree of irregularity of the overall three-dimensional system. The code definitions fail to capture some irregularities, especially those resulting from the combination of *both* plan and vertical irregularities. Also, system irregularity does not depend solely on structural properties, but also on the characteristics of the earthquake excitation and the distortion in structural properties due to variable damage cracking.

Structural system irregularity affects the conditioning of the eigenvalue problem, where the condition number k(**X**) is defined as the absolute ratio of the largest to smallest eigenvalues. A set of eigenvalues of relatively equal magnitude show that there is little irregularity in the structure, whereas a large difference in extreme eigenvalues implies a greater degree of structural irregularity IR. These values can help identify lack of stiffness in one of the in-plane directions, excessive P-Δ corrections at one or more levels, and any situation where a higher stiffness is associated with a smaller mass or a smaller stiffness is associated with a larger mass.

Conclusion

The measurement scale for the irregularity levels produced by asymmetric structural properties is applicable to diverse structure types and can be used by code committees to specify the acceptable degree of irregularity for delineating regular and various irregular building categories.▪

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