Determination of Acceptable Structural Irregularity Limits for the Use of Simplified Seismic Design Methods

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ABSTRACT: Current NZ code regularity limits for structures are based on engineering judgement rather than on quantitative analysis. This paper describes a quantitative method to determine limits for structural irregularity for structures designed using different analysis procedures. In this method, a parameter such as the change in median response, or the increased probability of greater demand, may be computed and then limited to an acceptable level. Irregularity limits based on a specified level of confidence are selected and these are then proposed for use in design. The method is illustrated by an example considering mass irregularity.

1 INTRODUCTION

A structure is seismically regular if it has a uniform mass, stiffness, strength and structural form throughout the elevation and plan of the building. An irregular structure is simply one having a non-uniform distribution of any of these properties individually or in combination, in horizontal or vertical directions. A structure could be irregular because architectural design requirements call for non-uniformity of some sort. This is designed/planned use (DPU) irregularity. Common examples of this type are; a residential building having a car park at the basement and a corresponding less stiff first storey, an academic institution having a heavy library on one floor level, or a structure designed to have setbacks to meet boundary offset requirements. A structure could also be irregular due to non-planned effects (i.e. randomness or aleatory uncertainties) such as when people move around in a structure causing non-uniformity of mass, variation in material properties causing non-uniform stiffness or strength etc. For these reasons, no structure is perfectly regular all the time. What is important is not whether or not a structure contains irregularities, but the ability of the designer to estimate the likely demands on structures with the irregularity present at the time of earthquake shaking.

The ability to estimate the likely demands of structures with irregularities is dependent on the analysis method. For example, 3-D inelastic dynamic time-history analysis (i.e. Nonlinear Dynamic Procedure (NDP)) of a good 3-D structural model can consider all irregularity effects, and hence demands, directly. However, other techniques cannot necessarily capture or represent irregularity effects. For example, simple techniques such as the NZ Equivalent Static Procedure (which is Linear Static Procedure (LSP)); the Modal Response Spectra or Elastic Linear Time History Analysis (which are Linear Dynamic Procedures (LDP)); the pushover method (which is a Nonlinear Static Procedure (NSP)), or a Nonlinear Cyclic Procedure (NCP) that involves a push-pull analysis and shows cumulative demands, are simplified methods which are calibrated against the NDP for regular structures, but such calibrations have not always been carried out for structures with significant irregularity. Some of the analysis methods described above will provide better estimates of the demands of an irregular structure than others. For this reason, appropriate calibration is required for each analysis method.

The ability to estimate structural demands is also dependent on the model. For example, 2-D analysis may not capture response of significantly irregular 3-D structures well. Also, explicit floor diaphragm modelling may be necessary to adequately represent the behaviour.

Many studies have been carried out to study irregularity effects but they do not provide general methods for quantifying acceptable irregularity limits.

Worldwide codes specify regularity limits for structures designed using simple analysis methods. These limits have been developed based on engineering judgement rather than on quantitative analysis (SEAOC 1999). There is a need to quantify regularity limits so that a consistent level of accuracy may be specified for different irregularity types, or other rational methodologies may be used, for different analysis/modelling methods.

This paper seeks to address the need for rational quantification of regularity limits by

i) Developing a methodology for developing rational regularity limits, and

ii) Providing an example considering the demands based on the NZS1170.5 using the Equivalent Static Procedure (**ESP**) analysis method and known mass irregularities.

2 NZS1170.5 CURRENT CONSIDERATION OF MASS IRREGULARITY WITH ESP

The ESP has been used to design the majority of NZ structures in the past. According to NZS1170.5 (SNZ 2004) this method may be used in the design of:

- any structure less than 10m in height
- any structure with a fundamental period of less than 0.4s
- a structure satisfying regularity requirement with a period of less than 2s.

If the structure does not meet these requirements, then a more sophisticated and therefore expensive analysis method should be used.

NZS 1170.5 specifies that a structure is said to have weight (or mass) irregularity if the weight, W_i, of any storey is more than 150% of the weight of an adjacent storey. Researchers looking into vertical regularity, including Valmundsson (1997), Al-Ali (1998), Chintanapakdee (2004), and Michalis (2006), do not provide information relating to the appropriateness of the 150% value and it is not clear what degree of variation in response is likely for structures designed as being perfectly regular as compared to having the 150% mass irregularity for the ESP method.

3 STRUCTURAL FORM AND DESIGN METHODOLOGY

The development of the methodology is carried out with reference to mass irregularity and the nine story building described below. The building has been designed in two ways according to the NZS1170.5 Equivalent Static Method (SNZ 2004). The structure was designed as a shear structure with a continuous column representing all of the continuous columns in the structure (Sadashiva et al. 2007). Firstly, it has been designed to have the maximum possible code interstorey drift at all levels simultaneously (represented as **CISDR**). Secondly, it has been designed to have a constant stiffness (represented as **CS**) at all levels with the code drift limit at the critical (i.e. first) storey. The deformed shapes resulting from these methods are given in Figures 1a to 1e. The strength is permitted to vary for both the design models as required by the code.

4 INCORPORATION OF MASS IRREGULARITY

A regular structure was considered to have a constant mass at each floor level. The effect of mass irregularity was considered by varying the floor mass of one floor and keeping the other floor mass constant (same as that of regular buildings' floor mass). Two mass ratios; 2.5 and 5 times the storey mass for the regular structure were considered to evaluate the effect of the amount of mass. The eccentric mass was applied to the first, last level and mid-height for all the frames as shown in Figure 1f, 1g and 1h. Each time the mass was changed, the structure was redesigned according to the method described above to have the specified design (target) drift.

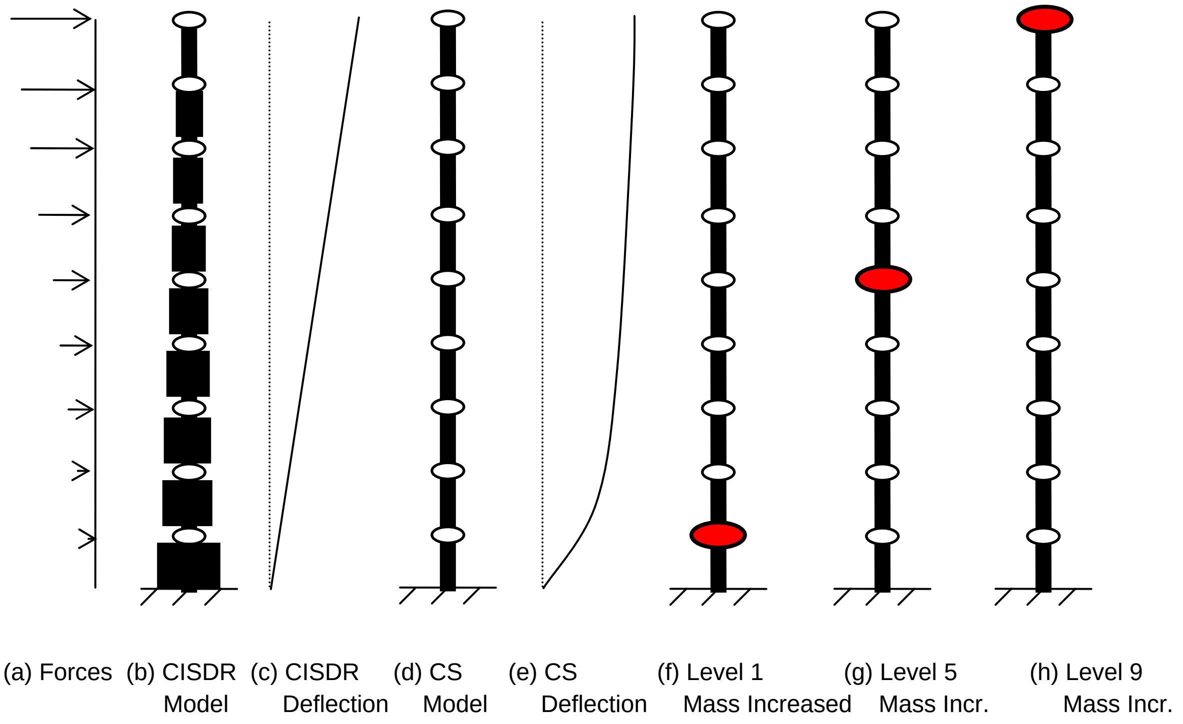


Figure 1. Deformed Shape for Different Methods and Mass Irregularity

To identify the different structural types, number of storeys, model type, irregularity location, and irregularity amount, for the structures designed according to the linear static procedure, a special notation of the form NS-M-L-(A) was used. For example, in 9-SF-9(2.5), the 9 storey structure (*NS*) is modelled (*M*) as a combination of shear and flexural beam (SF), having an additional mass (*A*) of 2.5, located (*L*) at the 9th floor. The regular structures are shown in the form: NS-M.

5 ANALYSIS METHOD

In this study, 20 SAC (SEAOC-ATC-CUREE) earthquake ground motion records, generated for Los Angeles having probabilities of exceedence of 10% in 50 years have been selected to carry out the inelastic time history analysis (**ITHA**). Response spectra were developed for each of the selected records and scaled by a scaling factor before applying them to the structure. A scale factor was chosen such that the spectral response gave the same design interstorey drift as the NZS 1170.5 code (2004) for an elastically responding single-degree-of-freedom oscillator designed for Wellington. Here, the ductility, μ, was assumed to be unity as was the S_p factor. A post elastic stiffness (bilinear) factor of 1 % and a tangent stiffness Rayleigh damping model with a damping ratio of 5 % were used in the first mode and in the mode corresponding to the number of storeys in the structure (Carr 2004).

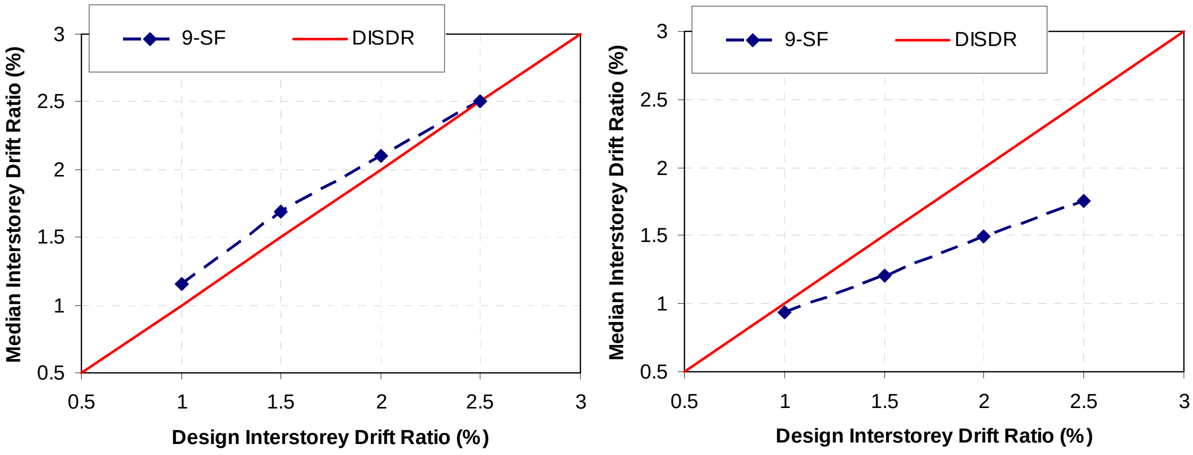
ITHA were carried out for the structure at different levels of ground motion intensity using the computer program RUAUMOKO (Carr 2004). The peak interstorey drift (**ISDR**) from all storeys in the structure was obtained for each record. The lognormal mean and standard deviation were used to describe the results from the record suite (Cornell et al. 2002).

For the irregular structure designed to the same target drift ratio, the period is different from that of the regular structure, so the design spectral acceleration is also different, but the same process described above is used to scale the earthquake records to the design spectral acceleration and to obtain the peak storey drift distribution.

It should be noted that there has recently been significant work regarding appropriate earthquake record selection for time history analysis. Baker (2007) has shown that random record selection may lead to unrealistic scaling and a large scatter in the absolute response. Also, records following the shape of the uniform hazard curve may incorrectly evaluate the response at different periods. As a part of this study, work is continuing on record selection. It is expected that the effect of record selection on relative response, such as that due to the effect of irregularity, may be less than that of the absolute response. This work will be published in subsequent publications.

6 EFFECT OF DESIGN METHOD

Figure 2(a) shows that the code on average non-conservatively estimates the median interstorey drift by about 8% for the CISDR model. On the contrary, the same structure, when designed as CS, shows that the code is conservative as shown in Figure 2(b).



(a) CISDR Model

(b) CS Model

Figure 2. Comparison between Actual and Code Response for Regular Structure

When irregularity is introduced, as shown in Figures 3 and 4, the median demands from the CISDR method may be less conservative than the design interstorey drift (**DISDR**), especially if the additional mass is located at Level 1. For the CS method, additional mass at all levels is more conservative compared to DISDR.

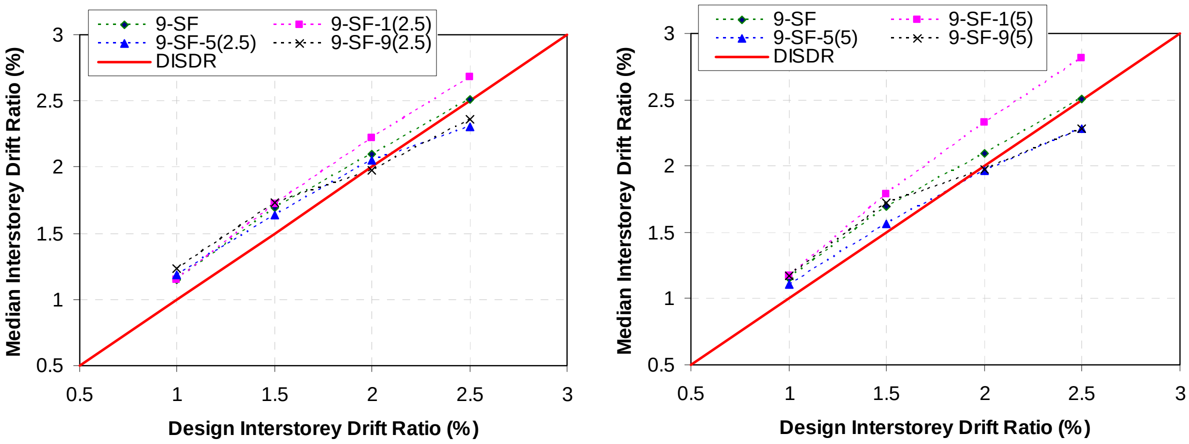
7 EFFECT OF IRREGULAR MASS AMOUNT AND LOCATION

The additional mass tended to increase the median interstorey drift response of the CISDR model compared to the regular structure by as much as 12% when the mass was located on the first level as shown in Figure 3. For the CS model, the top level was critical increasing the median demand by as much as 17% as shown in Figure 4. The same trends were observed for mass ratios of 2.5 and 5 times.

8 DETERMINATION OF IRREGULARITY LIMIT

For the storeys which caused the maximum increase in demand with each model, the increase is plotted against mass ratio in Figure 5. Such a plot could be developed considering the increased probability of greater demand, or some other relevant parameter. Such a plot may be used as part of a design method. For example, if it were decided that an increase in median response of no more than 10% were acceptable due to mass irregularity for all structural models and all locations, then a mass ratio of no more than 3 would be appropriate as shown in Figure 5.

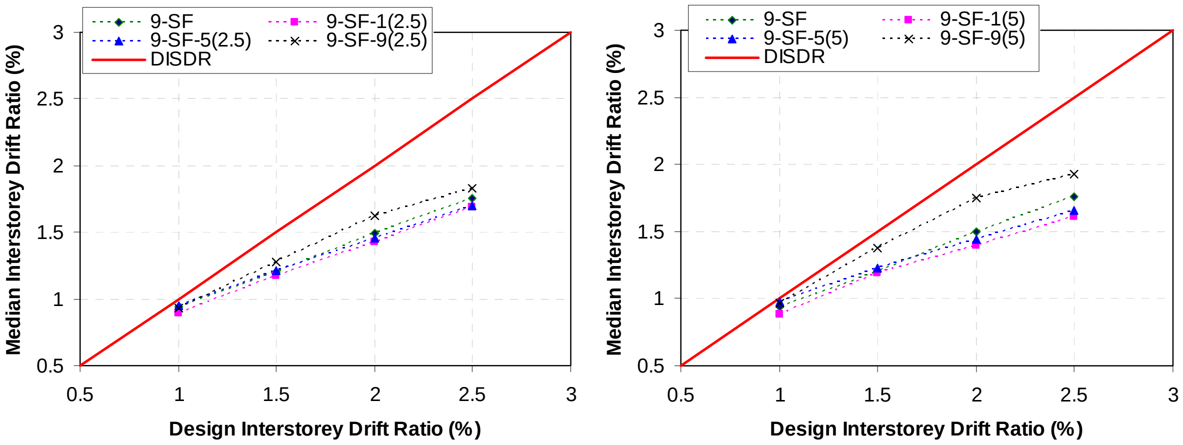
This simple methodology, which can be modified in many ways to consider different types of irregularity and different confidence levels on the increase in different demand quantities, is easy to develop and apply in design.



(a) Mass Ratio: 2.5

(b) Mass Ratio: 5

Figure 3. Nine Storey CISDR Model showing the Effect of Irregular Mass Amount and Location



(a) Mass Ratio: 2.5

(b) Mass Ratio: 5

Figure 4. Nine Storey CS Model showing the Effect of Irregular Mass amount and Location

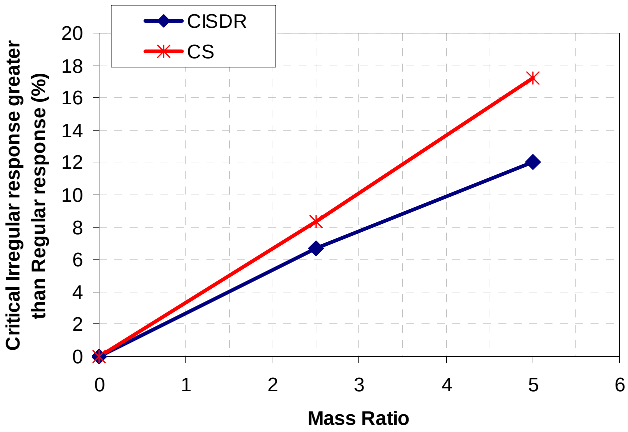


Figure 5. Determination of Irregularity Limit

9 CONCLUSIONS

This paper describes a quantitative method to determine limits for irregularity of structures designed using different analysis procedures. This method is illustrated using vertical mass irregularity for a 9 story frame. In particular it was shown that the effect of irregularity depends on the structural model used, the location and amount of the irregularity, and the analysis method used. The methodology proposed allows acceptable irregularity limits to be determined based on an acceptable increase in a specified response due to irregularity. The method is simple to use and sufficiently flexible enough to be developed in many ways. The increase in demand can be described in probabilistic terms and can be used in a probabilistic performance-based earthquake engineering (PBEE) decision making framework in the future.

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