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DETERMINATION OF IRREGULARITY LIMITS

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ABSTRACT :

Vertical and horizontal regularity provisions in the current New Zealand seismic design standard, NZS 1170.5 (SNZ 2004) are based on overseas codes. These regularity limits are based on engineering judgment rather than on rigorous analysis. This paper outlines a simple and efficient method of determining structural irregularity limits for structures designed using different analysis procedures. As an example, the methodology is applied to simple models of shear-type structures with different amounts of mass irregularity located at different locations within the structure, all designed in accordance with the Equivalent Static Method of NZS 1170.5, including *P*-Delta effects. These models were then analysed using inelastic dynamic time history analysis for the 20 SAC 10 in 50 earthquake records for Los Angeles. The additional median interstorey drift responses due to mass irregularity was computed which can be limited to an acceptable level. Irregularity limits for use in design can then be defined for a specified level of confidence.

KEYWORDS: Structural Irregularity Limits, Vertical Mass Irregularity, Design Standards

1. INTRODUCTION

A *regular* structure can be envisaged to have uniformly distributed mass, stiffness, strength and structural form. One or more of these properties can be irregularly distributed for architectural reasons. Common examples of architecturally planned (**AP**) irregularity include: a residential building with a car park in the basement that produces a correspondingly more flexible first storey, an office building with a heavy library at one level, or a shopping complex with setbacks to accommodate boundary offset requirements. A structure can also be irregular because of unplanned effects (i.e. randomness or aleatoric uncertainties). Examples of aleatoric uncertainty (AU) irregularity include deliberate and accidental rearrangement of loadings as well as material strength and stiffness variations.

Structures are never perfectly *regular* so designers routinely need to evaluate the degree of irregularity and therefore the demands that this places on the structure during an earthquake. They need reliable methods of quantifying the irregularity and using this to choose the least costly design and structural analysis methods. The most costly 3-D Inelastic Time-History Analysis (**ITHA**) method is generally considered to include every irregularity, although most designers only consider the ground motion probabilistically, leaving the structural properties and static loadings deterministic.

However, other analysis methods are less accurate for irregular structures. For example, the Equivalent Static (**ES**) Method defined in the New Zealand seismic design standard, NZS 1170.5 (SNZ 2004); the Modal Response Spectrum Method; and the Pushover Method are simplified methods which are calibrated against the ITHA for *regular* structures. However, these calibrations have not always been carried out for structures with significant irregularity. Some of the analysis methods described above are expected to 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 structural model. For example, 2-D analysis is generally not able to adequately represent the response of significantly irregular 3-D structures. Similarly, floor diaphragms may need to be modelled to adequately represent the behaviour.

Numerous studies have investigated irregularity effects but none have developed general methods for quantifying acceptable irregularity limits. This is reflected in most design codes specifying regularity limits for structures analysed using the simpler analysis methods. These limits have been specified from engineering judgment rather than developed using rigorous quantitative analysis. For example, the SEAOC blue book (1999), with recommendations similar to that in NZS 1170.5, states that:

> *".. irregularities create great uncertainties in the ability of the structure to meet the design objectives of [the code] … These Requirements are intended only to make designers aware of the existence and potential detrimental effects of irregularities, and to provide minimum requirements for their accommodation….",* (C104.5.3),

and

> *"Extensive engineering experience and judgment are required to quantify irregularities and provide guidance for special analysis. As yet, there is no complete prescription for … irregularities"* (C104.5.1).

Hence, there is a need to quantify regularity limits so structures can be designed to have a consistent level of reliability for each type of irregularity and for each analysis or modelling method. This paper proposes a simple, efficient and rational methodology for quantifying regularity limits of structures. Its accuracy is then verified using ITHA for AP vertical mass irregularities.

2. NZS 1170.5 CURRENT CONSIDERATION FOR MASS IRREGULARITY

The ES method (including structural actions and displacement amplification due to *P*-Delta effects) has been used to design the majority of NZ structures. NZS 1170.5 permits the ES method to be used to design any structure less than 10 m high, or having a fundamental translational period of less than 0.4 s, or with a period of up to 2 s if certain regularity requirements are satisfied. If the structure does not meet these requirements, then a more sophisticated and therefore expensive analysis method needs to be employed.

Structures designed using NZS 1170.5 are considered to have mass irregularity when the seismic weight, W_i, of the structure and live loading in any storey is more than 150 % of the seismic weight of either adjacent storey. Researchers investigating vertical regularity, including Valmundsson (1997), Al-Ali (1998), Chintanapakdee (2004), and Michalis (2006), have provided little justification for the choice of the nominal 150 % limit. Most importantly, they do not provide information as required for the New Zealand code amplified methods.

3. STRUCTURAL FORM AND DESIGN METHODOLOGY

The following methodology is proposed to quantify irregularity limits for a range of degrees of irregularity:

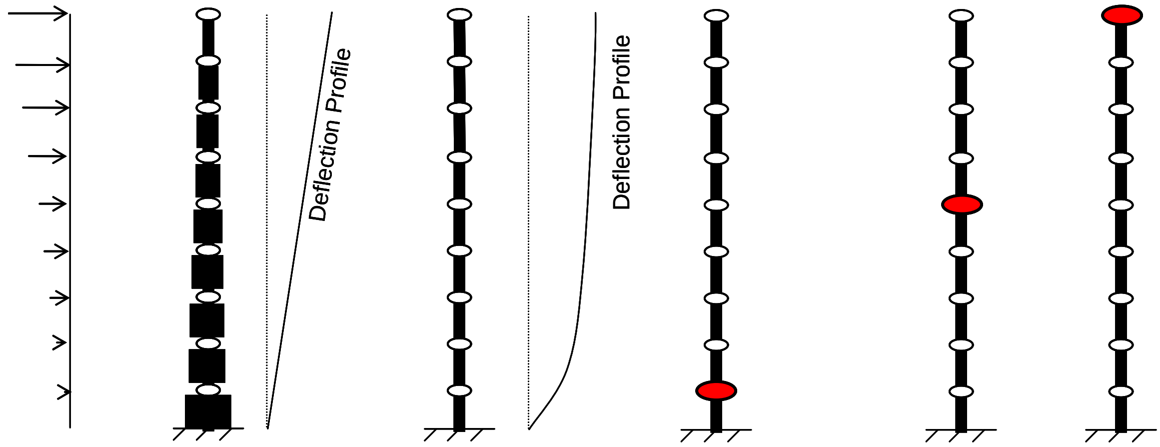
1. Define an engineering demand parameter that characterises structural damage. Interstorey drift provides the best indicator of the ultimate limit state being reached and will therefore be used in this paper.
2. Choose a set of interstorey drift capacities that span the range of values that could be used by designers (e.g. from 0.5% to 3%). Then for each target interstorey drift capacity and degree of irregularity:
    a. Design a *regular* structure using the ES method to the target interstorey drift capacity.
    b. Introduce the desired irregularity into the structure and use the ES method to design this new structure to the target interstorey drift. The mass irregularity considered here is most easily quantified as the ratio of the floor mass in this new structure to the corresponding floor mass of the *regular* structure.
    c. Evaluate the maximum interstorey drift for both structures using ITHA for a suite of design ground motions.
    d. Evaluate the performance for all of the ground motion records either a) as the difference between

the median responses of the two structures or b) as the probability that the demand for the irregular building is greater than the demand for the *regular* building.

3. The performance distributions for the chosen degrees of irregularity and target interstorey drift ratio may then be used to characterise the effect of both of these variables and select appropriate limits.

This methodology was applied to 3 and 9 storey shear type structures to assess its effectiveness for vertical mass irregularity.

There is no specification for the distributions of stiffness and strength within structures designed using the NZS 1170.5 Equivalent Static Method. Two classes of building were therefore chosen to represent the two extremes of design choice for stiffness. One class of building was designed for all storeys to have the target interstorey drift ratio (labelled **CISDR**) and the other class was designed for all storeys to have the same (constant) stiffness (labelled **CS**). These two models and their deflection profiles are shown in Figure 1 (b) and (c) respectively. Similarly, there is no specification of how much shear overstrength needs to be provided, so the shear strength at each level was the minimum required to resist the equivalent static design forces. Also, structures for which the base shear was governed by the lower limit (Equation 5.2(2), C5.2.1.1, NZS 1170.5) were eliminated to avoid the possibility of designing structures for different ductility ratios than the target ductility ratio of 4.



(a) Forces (b) CISDR Model (c) CS Model (d) Level 1 Mass Increased (e) Level 5 Mass Incr. (f) Level 9 Mass Incr.

Figure 1. Deformed Shape for Different Methods and Mass Irregularity

4. INCORPORATION OF MASS IRREGULARITY

The effect of mass irregularity was assessed by increasing the mass of one floor within each of the *regular* structures (i.e. those with the same mass at every floor level) to create the corresponding irregular structure. Four mass ratios were used, namely 1.5, 2.5, 3.5 and 5 times the mass at the other floor levels, and three positions were used, namely the first level, mid-height and the roof as illustrated in Figure 1 (d), (e) and (f) for the 9 storey structures. The natural periods and base shears of the irregular structures were slightly different from those of the *regular* structures because their stiffness distribution was adjusted to produce the same interstorey drift as the corresponding CISDR and CS *regular* structures.

5. STRUCTURAL MODELLING AND ANALYSIS

To avoid drift concentrations, each frame was modelled as a combination of a vertical shear beam and a vertical flexural beam (representing all the continuous columns in the structure) that was pinned at the base (Sadashiva et al. 2007). This type of model is referred to as shear-flexural-beam (SFB) and is shown in Figure 2. The post elastic stiffness (bilinear) factor for the beam elements was 1 % of their initial stiffness.

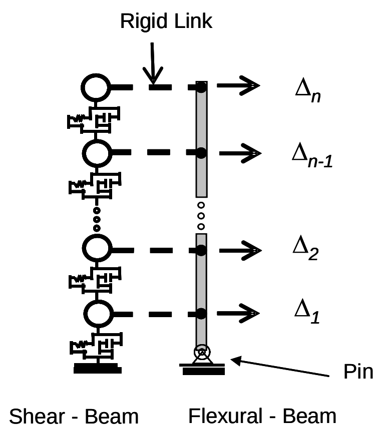


Figure 2. 1-D Shear-Flexure-Beam (SFB) Model

ITHA was used to calculate the peak interstorey drift ratio (**ISDR**) within the structure when it was subjected to a suite of scaled ground motion records. The RUAUMOKO (Carr 2004) computer program was used for the ITHA and the 20 SAC (SEAOC-ATC-CUREE) earthquake ground motion records for Los Angeles, with probabilities of exceedance of 10% in 50 years, were used for the ground motion suite. The lognormal mean and standard deviation of the peak ISDR for each record (Cornell et al. 2002) were used to represent the results for the whole suite.

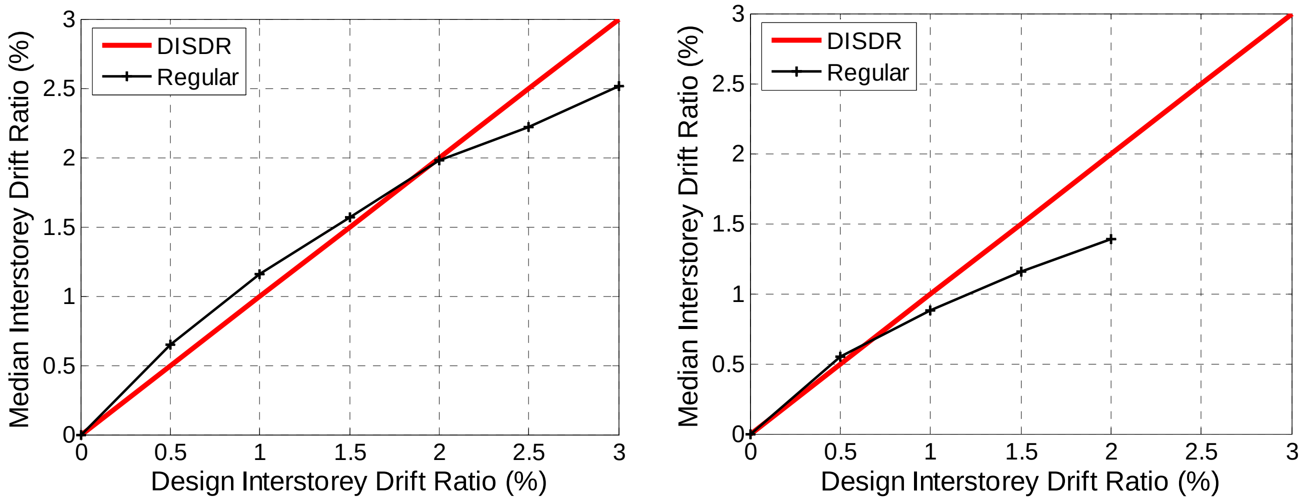
Baker (2007) has shown that random ground motion record selection can produce unrealistic scaling and increase the scatter of the absolute responses. Baker also suggests that records matching the shape of the uniform hazard spectrum may incorrectly evaluate the response at different periods. It is expected that the record selection and scaling will have less influence on the relative responses used in this study than on the absolute responses. The accelerations within each record were therefore scaled so that its single-degree-of-freedom elastic displacement response spectrum matched the design interstorey drift for NZS 1170.5 in the major city with the greatest ground accelerations, Wellington. The ductility, μ, and structural performance factor, S_p, were both unity.

Rayleigh damping has commonly been used to represent damping effects within multi-degree-of-freedom structures for several decades. However, with this damping model, the damping forces are seldom zero when the structure is stationary long after the earthquake has finished. Carr (2004) suggests that damping is likely to be more realistic if the instantaneous damping forces are the vector product of the Rayleigh damping matrix (calculated using the tangent stiffness matrix) and the instantaneous velocity vector. The first mode and the mode corresponding to number of storeys in the structure (Carr 2004) were nominated as the two modes with 5 % of critical damping to avoid sub-critical or negative damping.

6. COMPARISON BETWEEN ES DESIGN AND ITHA INTERSTOREY DRIFT RATIOS

The ES Method is based on the assumption that the set of equivalent static forces induce interstorey drifts that are comparable to those predicted using ITHA. If this assumption is true, the median ITHA interstorey drift ratio for the earthquake record suite will be close to the target or design interstorey drift ratio (**DISDR**).

Figures 3 (a) and 3 (b) show the differences between the design and median ITHA responses for 3 storey CISDR and 9 storey CS models respectively. For *regular* 3 and 9 storey CISDR models, Figure 3 shows that the ES method provides slightly non-conservative estimates of the interstorey drift ratio for DISDR < 2 %. (The other CISDR structures produced similar differences.) However, for CS structures, the ES method produced considerably more conservative designs for DISDR > 0.8 %. Figure 3 (b) was truncated at DISDR < 2 % because compliance with the NZS 1170.5 minimum base shear clause distorted the relationship.



(a) 3 Storey CISDR model (b) 9 Storey CS model

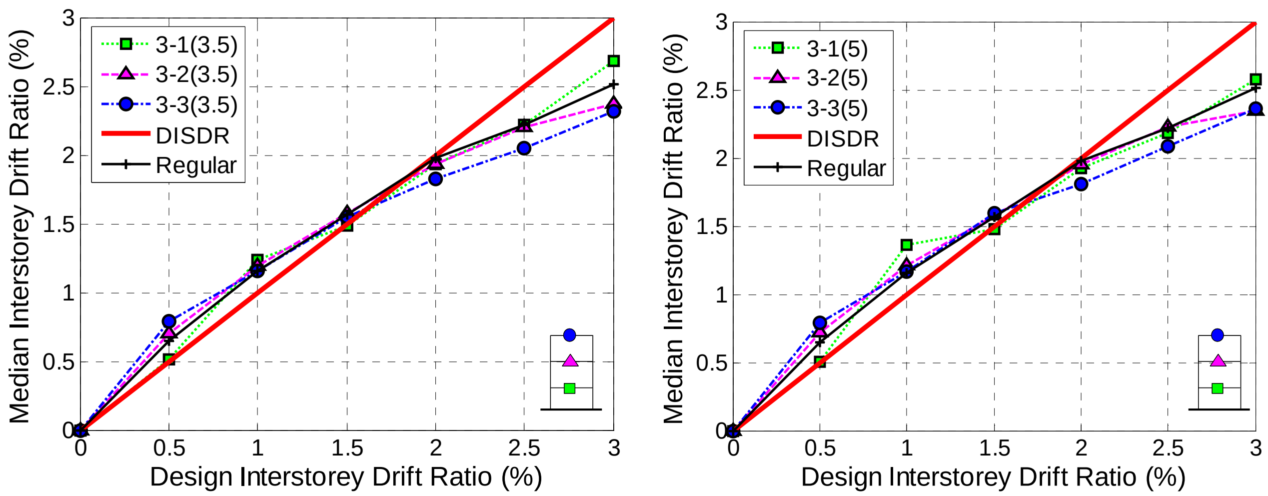
Figure 3. Comparison between Actual and Code Response for Regular Structure

7. EFFECT OF IRREGULARITY LOCATION AND MAGNITUDE

The median ISDR's for the structures with an increased floor mass at one level varied according to the position of the increased mass. Increasing the mass at the first level and at the roof appeared to produce greater interstorey drifts than when the mass was increased at the intermediate levels, so the comparisons for increased mass at these two levels and at the mid-height (i.e. the 2nd and 5th levels for 3 and 9 storey structures) are expected to provide representative responses. The response plot labels in the following figures have the format "N-L(Q)", where "N" refers to the number of storeys in the structure, "L" refers to the location (level) of the irregularity and "Q" defines the magnitude of the irregularity (mass ratio).

Figure 4 compares the median ISDR's for the CISDR model for a representative range of structures. Mass irregularities on either the first or topmost level produced greater ISDR's than the *regular* structure. However, the magnitude of mass ratio has less effect on the increase in demands than the position of the increased mass.

Figure 5 shows the effect of irregularity amount and locations on 3 and 9 storey CS model. For this model, the additional mass at the topmost level almost always produced higher ISDR's than the *regular* structure. Again, the position of the additional mass was more important than the magnitude of the increase.



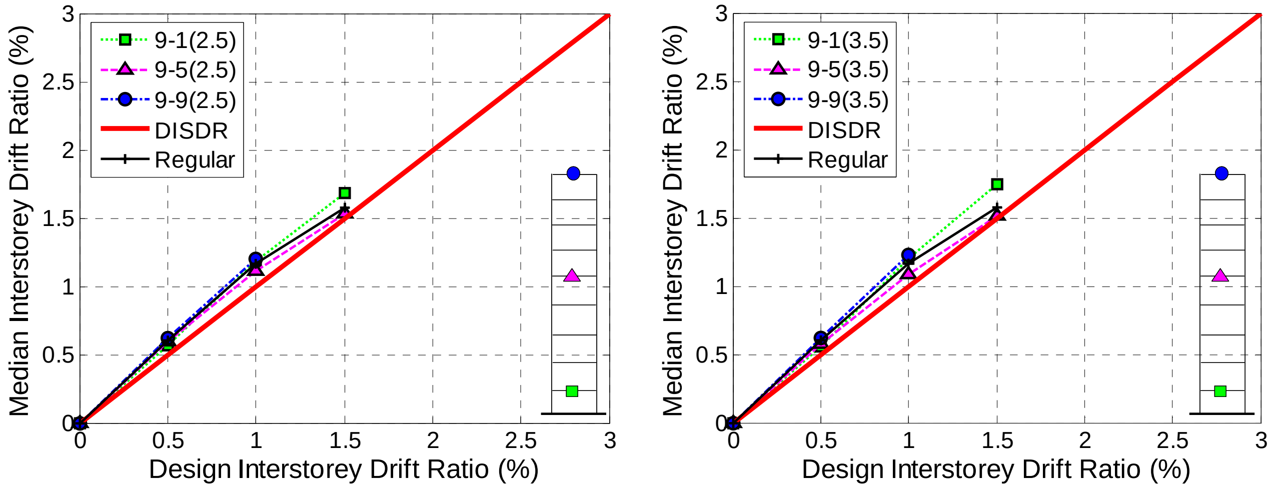


Figure 4. Effect of Irregular Location and Magnitude for CISDR model

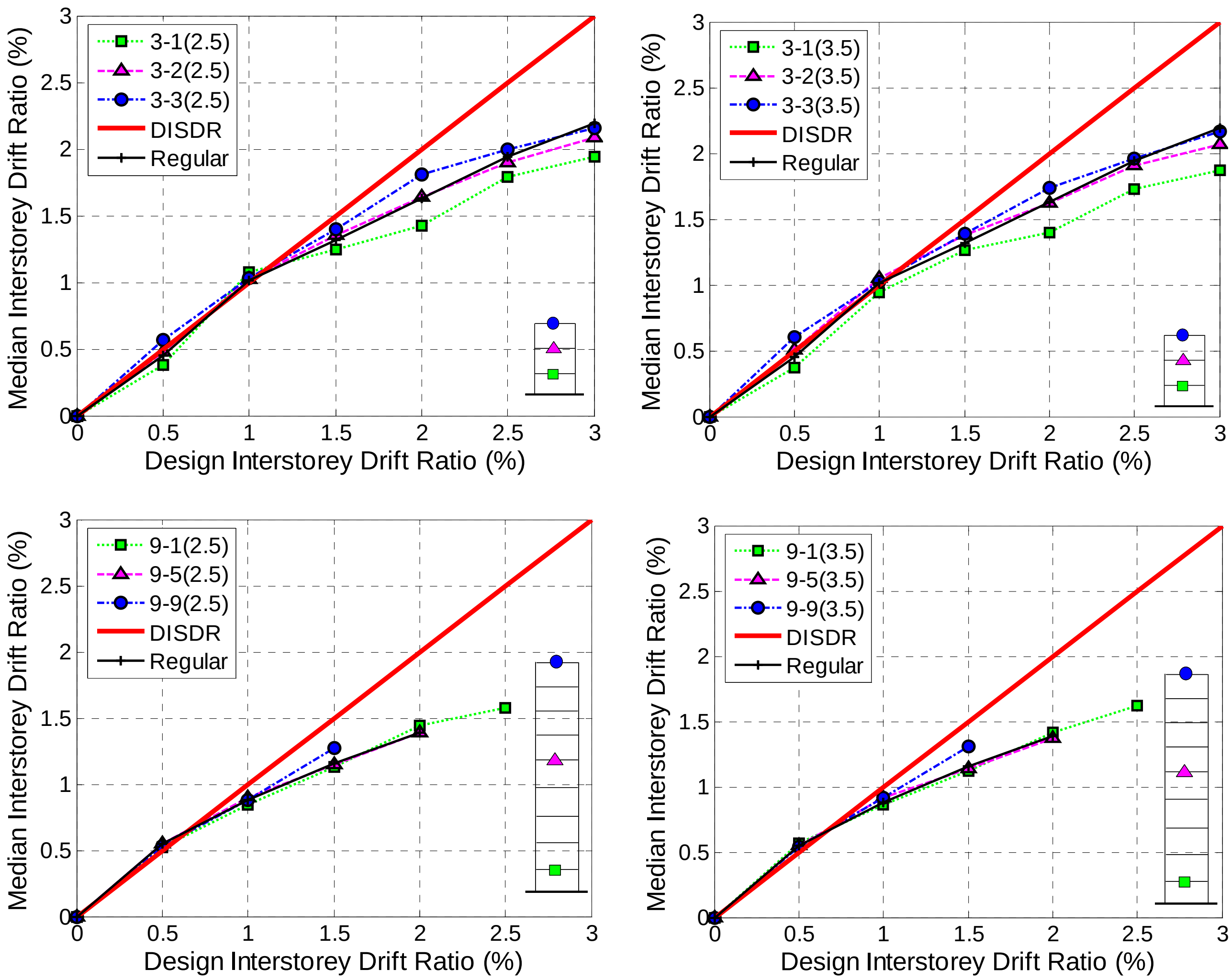


Figure 5. Effect of Irregular Location and Magnitude for the CS model

8. DETERMINATION OF IRREGULARITY LIMIT

For each building, the maximum additional (i.e. to the regular building) median interstorey drift was calculated for all irregularity locations. The maximum increase in demand is plotted in Figure 6 for each mass ratio. This conservative measure of the increase can be used to define a design method. For example, if it was decided that mass irregularity should produce less than 10% additional interstorey drift, then Figure 6 shows that the mass ratio needs to be less than 1.6.

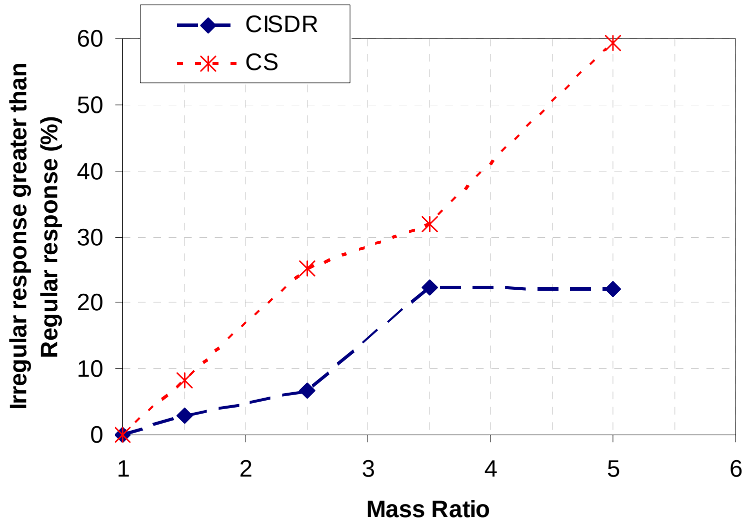


Figure 6. Determination of Irregularity Limit

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.

9. CONCLUSIONS

This paper proposed a novel method of quantifying irregularity limits for structures analysed using the simpler analysis procedures regulated by design codes. The new method was illustrated using vertical mass irregularity for 3 and 9 storey frames. Mass ratios of 1.5, 2.5, 3.5 and 5 times the floor mass of a *regular* structure were applied at first, mid-height and topmost levels of a redesigned structure to ascertain the median increases in interstorey drift responses. It was shown that the effect of irregularity depends on the structural model used, the irregularity locations and the analysis method used for the design. The proposed methodology allows acceptable irregularity limits to be determined from an acceptable increase in a specified response. The method is simple to use and sufficiently flexible enough to be developed in many ways and applied in design procedures.

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