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ASYMMETRIC-PLAN BUILDINGS: IRREGULARITY LEVELS AND NONLINEAR SEISMIC RESPONSE

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ABSTRACT

Results from both linear and nonlinear dynamic analyses exploring the seismic torsional behaviour of a multi-storey RC frame structure asymmetric in plan and regular in elevation are reported. Based on the obtained findings, the conceptual gaps in the current prescriptions given by the OPCM3431 and the EC8 on the evaluation method for the irregularity level produced by the mass and stiffness asymmetry and on the definition of the range of applicability of the linear analyses methods are identified. Comments on the code prescriptions relative to the number of accelerograms needed in the nonlinear time-history analyses and on the proposed method for modifying the seismic response obtained with a pushover analysis in order to account for the torsional behaviour of asymmetric-plan buildings are also presented. Possible proposals for a code provision are finally suggested.

KEYWORDS

Asymmetric-plan, irregularity level, evaluation, nonlinear dynamic response.

1 INTRODUCTION

Asymmetric-plan buildings, namely buildings with in-plan asymmetric mass and strength distributions, are systems characterized by a coupled torsional-translational seismic response. This particular behaviour under earthquake excitation usually leads to classify such type of buildings as irregular systems. Difficulties related to the study of their seismic response can be identified as follows: first, the identification and measure of the irregularity level produced by the asymmetry; second, the selection of the appropriate linear or nonlinear analysis method that can be used to evaluate the seismic demand; finally, the improvement and the extension of the pushover methods, originally proposed for regular structures, to the case of systems characterized by torsional seismic behaviours. The prescriptions on these issues proposed by the Italian code OPCM3431 "Technical Code for Seismic Design, Assessment and Retrofit of Buildings" (2005) are basically the same as those given in EC8 part 3 "Assessment and Retrofitting of Buildings" (2004). More specifically, as for the identification of the asymmetry, only general and qualitative rules are given by OPCM3431, which classifies buildings as regular only if both lateral stiffness and mass distributions are "approximately symmetrical" in plan with respect to two orthogonal axes. Furthermore, EC8 prescribes a limit on the value, both, of the structural eccentricity e_0 between the centre of mass and the centre of stiffness, and of the ratio between the torsional radius r and the radius of gyration l

of the floor mass in plan. As for the applicability of the linear analysis methods, both OPCM3431 and EC8 prescribe that the strengths should be distributed so as to produce uniform inelastic demands in the resisting elements of the structure. An estimation of the inelastic demand can be obtained by evaluating, for all the primary elements of the building, the ratio ρ_i between the bending moment demand calculated from a linear analysis and the corresponding capacity. In the evaluation of such uniformity, EC8 includes all yielded elements (with ρ_i values greater than 1), while OPCM3431 only those that go well into the nonlinear range (with ρ_i values greater than 2). It is important to note that this applicability condition for linear analysis methods applies to all buildings, regardless of the shape of their plan; as a matter of fact, no specific requirements for the case of asymmetric-plan buildings are given by either code.

Finally, on the use of pushover methods, while OPCM3431 does not apply any kind of restriction to asymmetric-plan buildings, EC8 prescribes to increase the displacements of the stiff/strong side obtained with a pushover by amplification factors based on the results of an elastic analysis. This prescription was supported by studies reported in Peruš and Fajfar (2005), Marušić and Fajfar (2005), and Fajfar (2005), which demonstrated that the elastic amplification of the displacements at the edges of the plan with respect to the displacement at the centre of mass can be used as a rough estimate also in the inelastic range.

The objective of the present paper is to show, through the analysis of a selected case study, the conceptual gaps in the current prescriptions given in OPCM3431 and EC8 on asymmetric-plan buildings. Suggestions for possible improvements of the identification and evaluation methods are also presented.

2 CASE STUDY

The case study selected for the investigation is the two-storey RC building shown in Figure 1, comprising a shear-beam frame structure with rigid diaphragms at each floor. The system is regular in elevation and asymmetric in plan because of the eccentricity in the x-direction at each floor between the centre of stiffness *CS*, located at the geometrical centre of the plan, and the centre of mass *CM*. Periods and participating mass ratios of the elastic modes of the system, whose shapes are shown in Figure 2, are reported in Table 1. Because of the asymmetry in the y-direction only, the first and third modes are coupled, while the second one is pure translational in the x-direction.

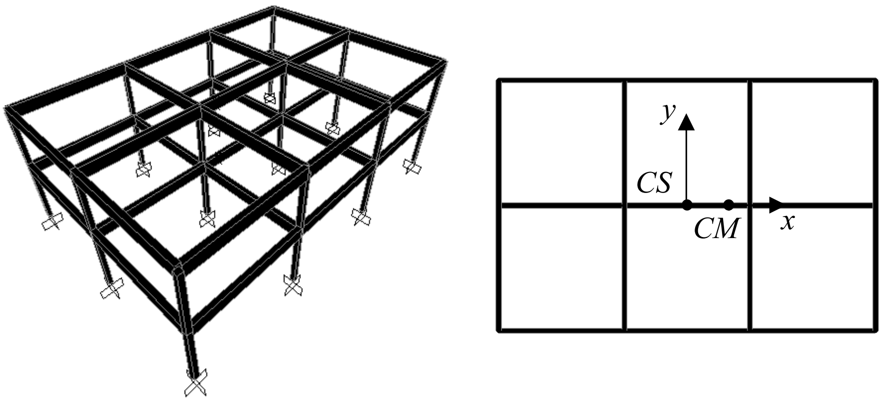

Figure 1. Studied two-storey frame RC structure: 3D view and plan.

The strengths of the resisting elements are designed for the seismic load combination so as to generate a uniform ρ_i distribution, characterized by a ratio between the maximum and minimum values ρ_{max} and ρ_{min} lower than the limit of 2.5 prescribed by OPCM3431. More specifically, the two ρ_{max}/ρ_{min} values corresponding to earthquakes exciting the structure in the x and y directions are equal to 1.89 and 1.73, respectively.

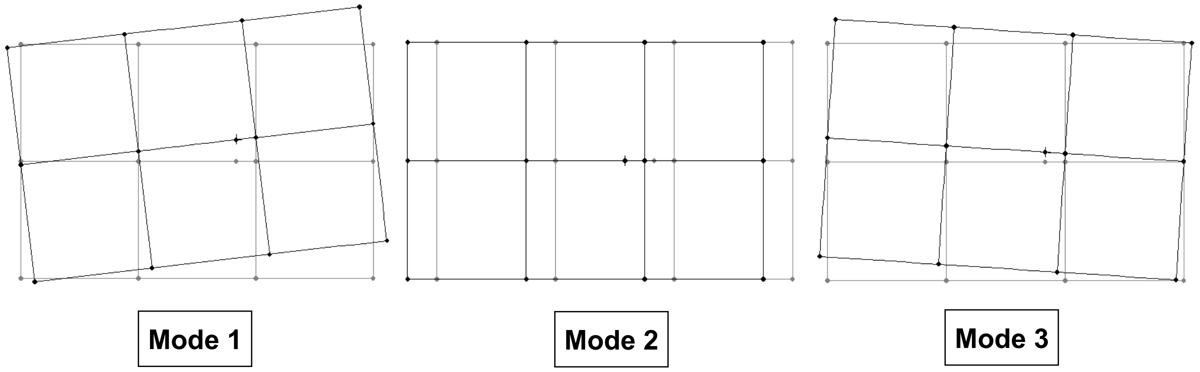

Figure 2. Deformed shapes at the roof of the first three modes of the structure.

Table 1. Periods and modal participating mass ratios.

	Mode 1	Mode 2	Mode 3
T [s]	0.70	0.62	0.56
M_{ux} [%]	0	93	0
M_{uy} [%]	52	0	41
M_{rz} [%]	78	0	15

Table 2. Natural accelerograms selected for the dynamic analyses.

Earthquake	Date	Station	Primary component *PGA* [g]	Secondary component *PGA* [g]
Friuli	1976-05-06	Tolmezzo-Diga Ambiesta	0.34	0.30
Montenegro	1979-04-15	Ulcinj-Hotel Albatros	0.35	0.28
Campano Lucano	1980-11-23	Bagnoli-Irpino	0.28	0.21
Campano Lucano	1980-11-23	Sturno	0.31	0.21
Umbria-Marche	1997-09-26	Nocera Umbra	0.51	0.45
Izmit	1999-08-17	Izmit-Meteoroloji Istasyonu	0.32	0.23
Duzce	1999-11-12	LDEO Station n° C0375 VO	0.74	0.48

In the nonlinear analyses, performed to evaluate the inelastic response of the structure, the resisting elements are modelled as beams with plastic hinges at the ends, with elasto-plastic hysteretic behaviours. The yielding bending moment values of the column hinges in the x and y directions are considered as non-interacting between them and with the axial force.

In both linear and nonlinear analyses, a Raleigh model is used for the viscous damping matrix, whose mass and tangent stiffness matrices coefficients are set to have modal damping ratios equal to 5% at the first and third period of the elastic system. The acceleration time-histories selected for the dynamic analyses are the seven unscaled natural accelerograms defined in Iervolino *et al.* (2007), compatible with the response spectrum type A with *PGA* intensity equal to 0.35g. The main properties of the records are briefly reported in Table 2.

3 ANALYSES RESULTS

On the selected case study two sets of analyses are carried out. First, linear modal response spectrum analyses are used to evaluate the coupling level between the rotational and translational response of the system produced by the in-plan asymmetry. Then, linear and nonlinear time-history analyses are used to study the seismic behaviour evolution from elastic to inelastic range, and also to evaluate the response sensitivity to the exciting accelerograms.

3.1 Response spectrum analyses

In general, the asymmetric-plan building irregularity results in the coupling of the torsio-translational behaviour, producing non-uniform seismic demands in the resisting elements of the system. Such coupling depends, in turn, by the significance of the higher modes contribution: in fact, it can be easily observed that, with the increase of the coupling, more than one mode is needed to excite the translational mass of the system.

However, it is worth noticing that, on the basis of this evidence, the irregularity in the demand does not depend solely on the properties of the building, as indicated both in OPCM3431 and EC8, but also on the properties of the seismic excitation. The single mode contribution, in fact, depends both on the associated participating mass ratio and on the frequency content of the seismic excitation as well.

This can be easily seen in the plot of Figure 3, where the OPCM3431 response spectra of three different ground types are shown. Looking at the two periods T_2 and T_3 of the coupled modes of the studied building, it is observed that for two different spectra, *e.g.*, type D and type A, the relative contribution of the modes is different: for type D the two modes have the same contribution, while for type A the two modes have different contributions.

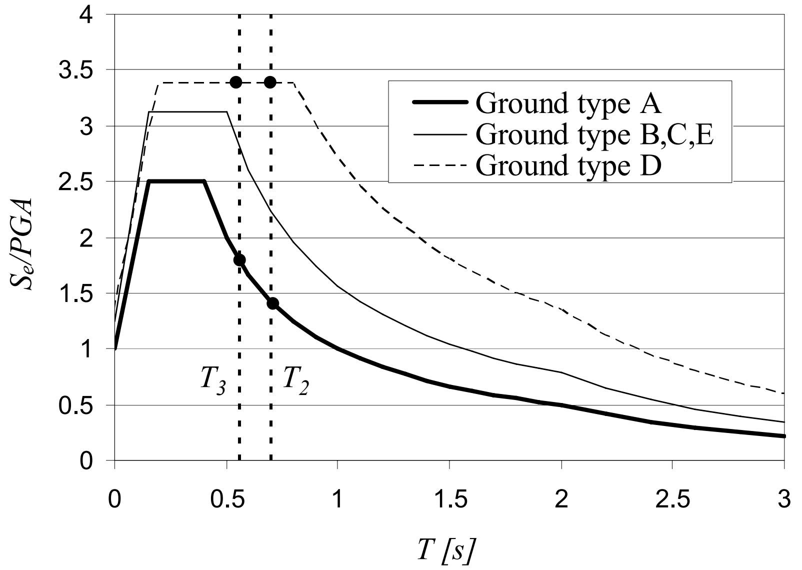

Figure 3. OPCM3431 response spectra with the periods of the coupled modes of the studied building.

One way for estimating the importance of the higher modes in global terms could be to evaluate the ratio between the seismic base shear associated to the first coupled torsional-translational mode in one direction and the total seismic base shear acting in the same direction.

Thus, a simple modal response spectrum analysis would suffice to measure the irregularity level of the building, while weighing the seismic excitation effects on the asymmetry of mass and stiffness distributions.

In the studied case, values of the base shear ratio ranging between 65% and 75%, depending on the ground type considered, are obtained.

3.2 Time-history analyses

According to EC8, if ρ_{max}/ρ_{min} is lower than a certain value (2.5 for OPCM3431), then the distribution of the inelastic demands, as measured by the ρ_i, is considered as uniform. This allows to use a linear analysis to evaluate the seismic demand in the resisting elements of the building. In this prescription, there is the implicit assumption that, if the inelastic demands are uniformly distributed, then the building behaves regularly, in the sense that the elastic response shape does not significantly change when the building enters the nonlinear range. This implies that the seismic demand evaluation (in terms of deformations) obtained from the linear analysis can be considered as representative of that in the nonlinear range.

One of the peculiarities of the seismic response of asymmetric-plan buildings is that the maximum demand is not attained at the same time in all the elements of the structure: this is due to the higher modes effects, that is, to the torsio-translational behaviour characterizing their seismic motion. For such systems, even if their ρ_i distribution is uniform, the structure does not enter the nonlinear range in a uniform fashion. In such case, it can be seen that the seismic response cannot be identified as regular. This is the case of the investigated asymmetric-plan building, which, notwithstanding its ρ_{max}/ρ_{min} largely lower than 2.5, shows a seismic response shape in the nonlinear range different from the linear one.

In Figure 4, the response of the building to the Montenegro earthquake (Yugoslavia, April 15, Ulcinj-Hotel Albatros station) is shown. In the plots, the envelopes of the maximum displacements in the direction of asymmetry (the y-direction) of the four frames at the second floor of the structure are reported. More specifically, in the two plots the absolute displacements u_y and the normalised values with respect to the displacement at the centre of mass $u_{y,\ CM}$ are shown, respectively. In addition to the nonlinear displacements, in each plot the elastic response of the building to the same accelerogram is also reported for comparison.

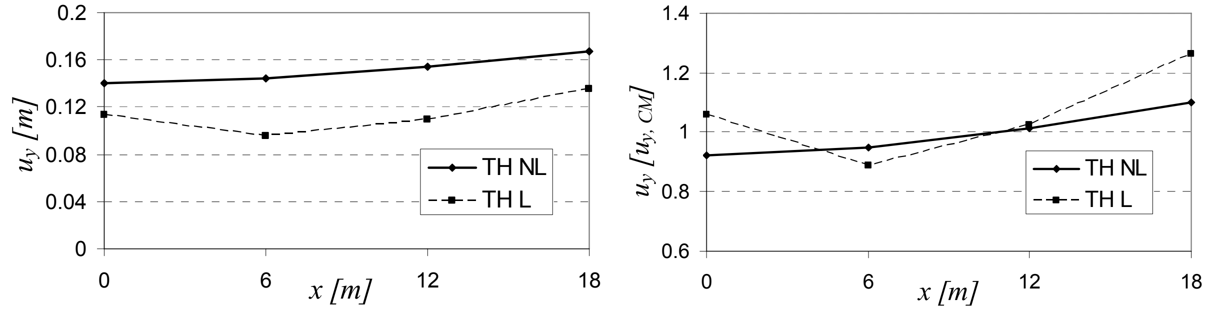

Figure 4. Response of the system to the Montenegro earthquake: envelopes of the roof maximum displacements in the y-direction obtained from nonlinear (TH NL) and linear (TH L) analyses, shown as absolute values (left) and normalised with respect to the centre of mass displacement (right).

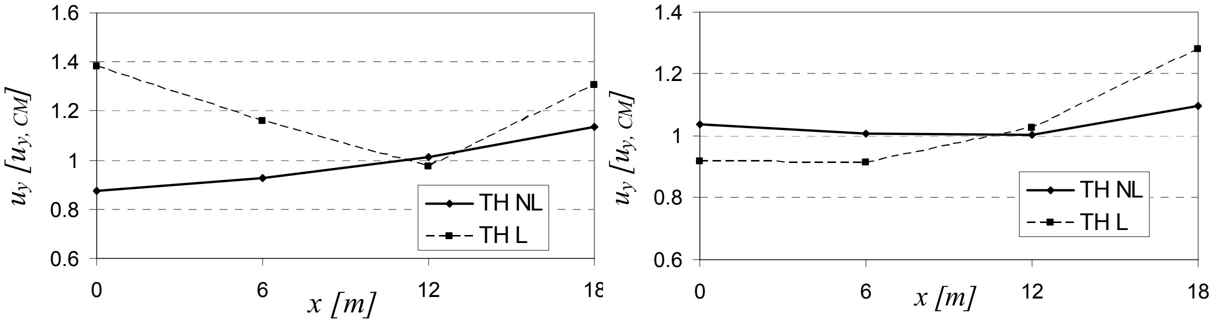

Figure 5. Comparison of the responses under different earthquakes normalised with respect to the centre of mass displacement: Campano Lucano (left) and Umbria Marche (right).

On the basis of these results, general observations on the behaviour of asymmetric-plan buildings can be done. First, in some cases the inelastic deformations of the system can result higher than the elastic ones, meaning that the linear analysis can underestimate the actual inelastic demands in the elements of the structure. Second, the shape of the system response changes between linear and nonlinear range. The elastic one, in fact, is usually more affected by in-plan rotations (see, for example, Lucchini et al., 2009): the more curved envelope shows amplifications with respect to the displacements at the centre of mass on both the rigid and flexible side of the plan, which are usually absent in the nonlinear response.

From such considerations, it can be concluded that, for asymmetric-plan buildings, if the inelastic demand is estimated as significant (*e.g.*, as proposed by OPCM3431, if the ρ_i are greater than 2), regardless its distribution (as measured by ρ_{max}/ρ_{min}), a nonlinear analysis should always be used to evaluate the seismic demand.

In Figure 5, the envelopes of the maximum displacements produced by the Campano Lucano and the Umbria Marche earthquakes, respectively, are reported. From the comparison between the two curves the dependence of the shape of the system response on the selected exciting accelerogram can be clearly noticed: on the flexible side of the plan, in fact, either amplifications or deamplifications can be experienced by the system in the nonlinear range.

Such dependence can be also observed in the plot of Figure 6 that reports, both for the linear and the nonlinear response (denoted with solid and dashed lines, respectively), the mean and the mean plus/minus one standard deviation values of the *normalised* maximum displacements (which shows the displacement *shape*), evaluated in the *y*-direction for all the seven earthquakes in Table 2.

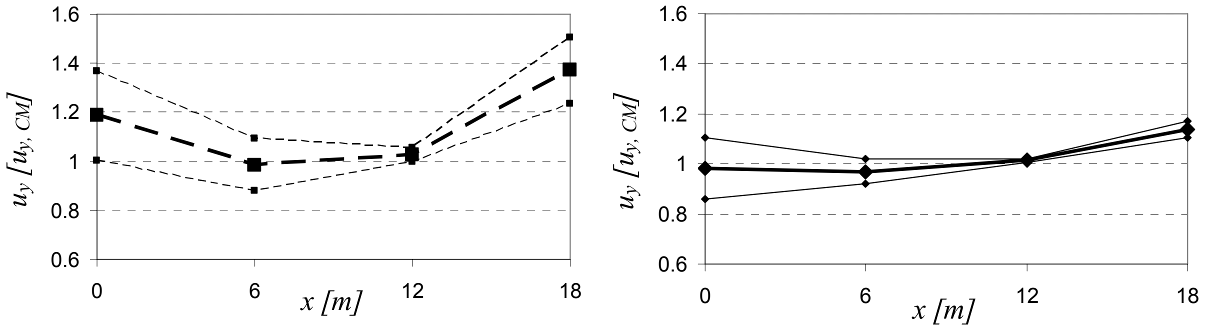

Figure 6. Mean and mean plus/minus one standard deviation values of the *normalised* maximum displacements in the *y*-direction evaluated for the seven earthquakes in Table 2, as obtained from linear (left) and nonlinear (right) analyses.

Even if the response *shape* tends to show less variability in the nonlinear range – *i.e.*, its standard deviations decreases – however, it still depends on the excitation characteristics: it is important to notice, in fact, that for regular buildings characterized by pure translational behaviours the standard deviation of the normalised displacements is always equal to zero, as the in-plan response *shape* does not depend on the excitation.

Based on this finding, it can be stated that when nonlinear time-history analyses are used to evaluate the seismic demand of asymmetric-plan buildings, because of the significant sensitivity of the response shape to the selected record, a larger number of accelerograms than that requested for regular buildings should be prescribed by the code.

Observing the plot of Figure 6, another interesting result can be found: the mean value of the normalised displacement evaluated with the linear analysis is always higher than the nonlinear one. This means that the inelastic displacements amplifications at the edges of the plan can be conservatively approximated by the elastic ones. This finding actually confirms the EC8 prescription that requests to increase the displacement of the stiff/strong side obtained with a pushover with an amplification factor based on the results of an elastic analysis. However, based on this code prescription, while the displacements are clearly obtained through the amplification factors, it is not clear how other quantities of interest (*e.g.*, element forces or chord rotations), nonlinearly dependent on the displacement, can be obtained.

4 POSSIBLE PROPOSALS FOR A CODE PROVISION

Dynamic analyses carried out on a selected case study of a mass-asymmetric multi-storey frame building led the authors to highlight conceptual gaps of both OPCM3431 and EC8 seismic codes in the following general issues related to the evaluation of asymmetric-plan buildings:

- the estimation of the irregularity level of the seismic behaviour of the building;
- the use of the ρ_i uniformity as a parameter evaluating the regularity in the resistance distribution and identifying the range of applicability of linear analyses;
- the evaluation of the number of accelerograms to be used in nonlinear time-history analyses;
- the modification procedure of the pushover method to account for the torsional behaviour.

Based on the results obtained in the investigations, the following suggestions are proposed by the authors for improving the code prescriptions:

- the irregularity produced by the asymmetric elastic properties of the building could be measured by evaluating the ratio between the contribution $V_{b,1}$ given by the first coupled mode in one direction and the total seismic shear $V_{b,tot}$ acting at the base of the structure in the same direction; this parameter, which can be calculated with a simple modal response spectrum analysis, can measure both the coupling level of the building behaviour and the influence of the earthquake properties on the significance of the higher modes effects;
- when significant nonlinearity is expected (*e.g.*, as proposed by OPCM3431, if $\rho_i \geq 2$), regardless the uniformity of the estimated inelastic demand distribution (as measured by ρ_{max}/ρ_{min}), the building should be evaluated with a nonlinear analysis; apart from the regularity of the resistance distribution with respect to the seismic demand, mass and stiffness asymmetric configurations produce an irregular response, namely an irregular evolution of the nonlinear damage that cannot be evaluated with a simple linear analysis;

- the minimum number of accelerograms requested in the nonlinear time-history analyses should be larger than that prescribed by the code for regular symmetric-plan buildings; in fact, unlike symmetric systems, those asymmetric in plan show a response shape significantly sensitive to the exciting record; however, the authors believe that further investigations are still needed to define such minimum number;
- more exhaustive explanations on how to modify the pushover analysis results based on the elastic analyses should be given by the code when dealing with response quantities that do not depend linearly on the displacements (*e.g.*, the element forces or the chord rotations) need to be evaluated.

A possible procedure for selecting the analysis type based on the first two points listed above, is shown as a flow-chart in Figure 7.

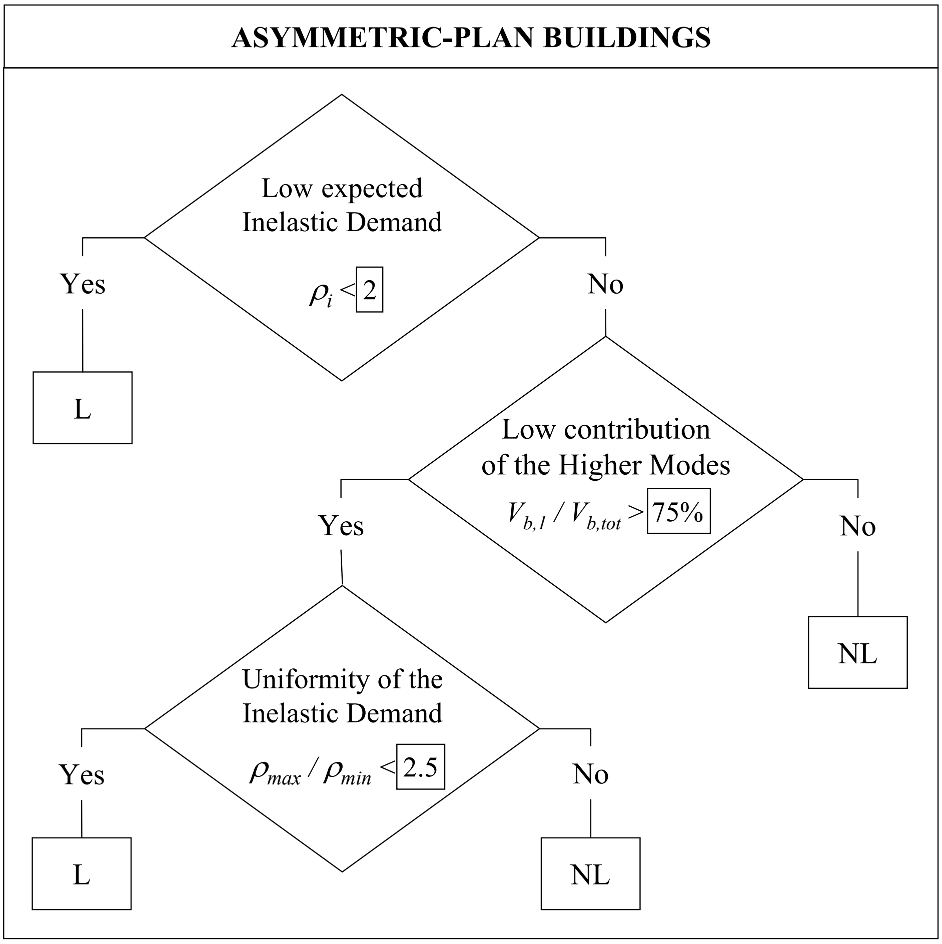

Figure 7. Proposal of requirements for selecting linear (L) or nonlinear (NL) analysis methods in the evaluation of asymmetric-plan buildings.

5 ACKNOWLEDGEMENTS

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