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Effects in Conventional Nonlinear Static Analysis: Evaluation of Control Node Position

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ABSTRACT

The nonlinear methods of analysis are the most indicated ones to carry out the vulnerability assessment of existing Reinforced Concrete (RC) buildings. Notwithstanding nonlinear approaches strongly depends by the knowledge level of building, they allow to obtain the effective response of structure, due to the combined effect of both dead and seismic loads.

However, these methods are based on conventional choices that, in some cases, can modify the results that are affected of a significant uncertainty level. Concerning to nonlinear static method, one of the fixed point at the base of analysis is the choice of control node (point in which the displacement of the structure under horizontal load is monitored) coincident with the centre of mass of last storey of building. This assumption is significant when, in order to verify the structural capacity with N2 method, an equivalent Single Degree of Freedom (SDoF) system is considered, neglecting the real variability of centre of mass position, provided by the accidental loads.

In the present work, it will be shown as the structural capacity (in terms of displacement at Life Safety Limit State) with reference to several cases of existing RC buildings can be strongly affected by the choice of the control node position. In particular, 28 existing RC buildings were analysed. These are part of a large sample of example cases made according to geometric and mechanics features of real existing buildings. The peculiarity of the “ideal” buildings consist in an irregular in-plan shape but with dynamic properties such as to allow the applicability of pushover analysis and, consecutively, the application of N2 method. In order to optimize the procedure of choice of control node, a parametric formulation is proposed, depending by dimensionless geometric features, able to estimate the variability of capacity curve at variation of control node position.

This approach is mainly finalized to expeditious estimate of structural behavior for RC buildings of urban aggregate and it is a base for formulation ad hoc to evaluate the structural response of dynamic irregular buildings.

1. Introduction

The vulnerability analysis and structural assessment of RC existing buildings are important focuses of interest by scientific community, which aim to preserve the building stock that has important historical and artistic value. Generally, existing RC buildings are designed using old technical codes, which do not take into account the effects due to seismic events.

The methodology to carry out a vulnerability analysis is not well defined, cause of the uncertainties related to knowledge of each aspect, as geometric and mechanics features, of building study.

European Building code (EC8) [1], like Italian Code [2–3] provide a “performance based approach” with some general rules and guidelines, which engineers should follow, in order to define the seismic vulnerability of existing buildings. Final aim of this methodology is the evaluation of structural performance in terms of building capacity and compare it with seismic demand.

The first phase of procedure regards to preliminary knowledge in which the aim is find precise historical information in regard of building study as original design drawings, information about foundations and ground conditions, dimensions and cross-sectional properties of building elements, properties of materials, constructive details.

In order to have a complete framework on existing building, information collected should be completed through in-situ investigation. In particular, according with a preliminary investigation plan, an accurate relief and some experimental destructive and non-destructive tests on materials must be carried out [42,43].

With general framework obtained by previous work steps, relying on quantity and quality of data collected, a *Knowledge Level* (KL) can be defined, which is directly related to a *Confidence Factor* (CF), index used

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to penalize the in situ materials strength.

After completing the knowledge process, the final scope is to verify the Safety Level of building analysed, considering all loads combination for the limit state of interest, as provided by codes.

For this goal, it is necessary to simulate structural behavior through an adequate numerical model on which seismic analysis is carried out.

Nonlinear analyses (static or dynamic) represent the most realistic approach for seismic analysis on RC existing buildings, as suggested in EC8– part 3, paragraph 4.1, in order to consider the nonlinear features of materials, sections and elements, which allows to predict with accuracy the structural behavior.

Results of nonlinear analysis is a capacity curve, expressed in terms of base shear vs. maximum displacement at defined limit state. Usually, maximum displacement corresponds to the one measured at *Center of Mass* (CM) of last floor of building study. This point is called "*Control Node*" (CN).

Safety level is defined as the ratio between structural capacity and seismic demand, through a particular procedure, reported in [1] and known as N2 method [4], briefly described to follow.

This method is a "Displacement Based" methodology [4], whose name derives from two distinctive features. Then, "N" which indicates that the method is Nonlinear and "2" which refers to use two different computational models of the structure: a *Multi-Degree of Freedom* (MDoF) model, on which a pushover numerical analysis is performed, and an "equivalent" *Single-Degree of Freedom* (SDoF) model, which is derived by the previous one trough proper manipulations.

After defining the numerical MDoF model and the elastic spectrum in pseudo-acceleration with established damping value, at limit state considered, pushover analysis is carried out using an unimodal load profile, according to the following relationship:

$$\mathrm{F} = \lambda(\mathrm{t})[\mathrm{M}]\{\Phi\} \tag{1}$$

where [M] is the diagonal matrix of the storey masses; {Φ} is a proper displacement shape vector of fundamental vibration mode (normalized with respect to the displacement of the CN) and λ(t) is a scalar parameter that controls the evolution of the load history. The limit of this application regard its applicability on irregular building, where higher modes are important and vector Φ is not representative of structure behavior. In this case, the procedure must be modified [33–34]

The capacity curve obtained for the MDoF system is then scaled in order to represent the response of an SDoF system having an equivalent mass $m^* = \{\Phi\}^{\mathrm{T}}[\mathrm{M}] = \Sigma\, m_i\Phi_i$,by applying the modal participation factor:

$$\{\Gamma\} = \frac{\sum m_i\phi_i}{\sum m_i\Phi_i^2} \tag{2}$$

In particular, both top displacements and base shears values are scaled for Γ, as indicated in the following relationships:

$$d^* = \frac{\mathrm{d}}{\Gamma} \tag{3}$$

$$F_b^* = \frac{F_b}{\Gamma} \tag{4}$$

where d* and F_b* indicate respectively top displacement and base shears values of SDoF system. This application depend by assuming a time-independent displacement shape.

The capacity curve of SDoF system is transformed into a simplified bilinear capacity curve characterized by a yield and an ultimate point as imposes, for example, by Italian Seismic Code.

The final capacity curve can be directly compared with the seismic demand evaluated for the SDoF system, through the elastic spectrum, expressed in the plane Acceleration vs. displacement, called "Acceleration - Displacement Response Spectrum" (ADRS) where the spectrum format is governed by the following equation:

$$S_a = \frac{F_b}{\Gamma m^*} \tag{5}$$

The seismic demand should be referred to the inelastic spectrum, in order to consider the inelastic features of the structural system and it can be obtained scaling the elastic design spectrum by a reduction factor R_μ, which expresses the overall structural ductility. R_μ is calculated as follow:

$$R_\mu = \frac{S_{ae}}{S_{ay}} \tag{6}$$

where S_{ae} is the value of elastic spectral acceleration for the period T* and S_{ay} is the spectral acceleration corresponding to yield force as well as acceleration capacity.

The N2 method has been extended for in-plan irregular building, amplifying the effect of NLS analysis in inelastic field, through a "torsional amplification" or a "corrective eccentricities", following several methods provides by scientific literature [35–39].

In the performance approach described, besides the difficulties related to collect the original documentation, carry out materials investigation and simulation of the real structural behavior, a main problem is represented by the applicability of nonlinear analysis. In particular, *NonLinear Static* (NLS), which usually provides accuracy results and well represents the envelope of all possible dynamic responses, is never applicable. NLS analysis can be used to replace a full *NonLinear Dynamic* (NLD) analysis, for its simple and fast application that reduce computational effort.

Conventional NLS analysis consists in the application of a proper lateral load profile (force or displacement) to the structure and then monotonically increasing it until the collapse mechanism is reached.

EC8 provides some general rules of NLS analysis applicability on RC buildings, as specified to follow:

- participating mass of fundamental vibration mode must be > 75% of total mass;
- analysis must be carried out using two load profiles that belong to two different load groups (Group 1: unimodal or inverse triangular load profile – Group 2: uniform, adaptive or multimodal load profile).

This procedure can provides inaccurate results, especially when case study presents strong irregularities in geometry (in plane or in height), in mass and in stiffness or when the building analysed has an elevate number of storeys.

Same code defines general rules of "conceptual design" to define the structural regularity.

For the regularity in plan, some prescriptions are summarized as follow:

- Building structure must be symmetric towards two orthogonal axis;
- In-plan configuration must be compact. *Re*-entrances are allows, in order to do not influence in-plan stiffness;
- In-plan stiffness must be enough greater than vertical elements stiffness. In this regard, in-plan shape as L, C, H, I, X must be carefully analysed, in order to assess the rigid floor assumption;
- The ratio between maximum and minimum dimensions of building must be < 4.

For the regularity in height, some prescriptions are summarized as follow:

- Each primary vertical element must extends along the height of building, from foundation to top storey;
- Stiffness and mass of each storey must be constant or can change without abrupt variation;
- *Re*-entrances of each storey must be < 20% of dimension