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A numerical procedure for modeling the floor deformability in seismic analysis of existing RC buildings

S. Ruggieri*, F. Porco, G. Uva

Department Dicatech, Politecnico di Bari, Via Orabona 4, 70125 Bari, Italy

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ABSTRACT

In the paper is presented a research study on floor system behavior in existing *Reinforce Concrete* (RC) buildings under horizontal actions. Generally, vulnerability analysis consists in the study of effective structural behavior of buildings, in order to carry out the assessment, comparing seismic demand and structural capacity. To this purpose, the hypotheses at the base of *Finite Element* (FE) numerical model, as rigid floor assumption, assume a primary role for the accurateness of seismic analysis results.

In the study, after carrying out a preliminary assessment on significant parameters, which influence the floor stiffness, a new numerical simplified procedure has been proposed. Starting by micro-models, made with solid elements, on several simple applications, the behavior of floor system in elastic field has been analyzed in terms of in-plane displacements and a thickness of an equivalent shell of orthotropic material has been defined, usable in macro-model of frame-shell elements.

Subsequently, using the procedure proposed, a real case of existing RC buildings has been investigated. The results of linear analysis have been evaluated through their comparison with those obtained by a model where the flexibility of slab is simulated with a more consolidate method like "strut model".

The numerical analyses carried out have enabled to give interesting indications about both the accuracy of rigid floor assumption and assessment of slab elements.

1. Introduction

The vulnerability assessment of RC existing buildings are one of the main problems in scientific literature in recent years. Especially in the most seismic European regions, as Italy, the building stock is designed through old codes, without considering the design rules provided by modern codes (capacity design, hierarchy of strength,…).

Additionally, the well-know problems related to inadequate quality of structural materials and execution, associated to concrete strength decay and durability due to environmental conditions, lead to a low performance of buildings towards seismic actions.

In order to analyze the real behavior of these structures and to choose the most suitable retrofit solutions, in modern seismic codes, as Eurocode 8 [11] and consequently some national codes [6,9], is provided a "performance based approach", in which they are analyzed the results obtained by nonlinear analysis on the structural FE model.

The most accurate analysis method is the *Nonlinear Dynamic* (NLD) analysis that, despite it is more reliable than other methods, it is rarely used in common engineering applications for its complexity and elevate computational effort. Furthermore, in this method are present several problems of applicability, as the difficult in the correct selection of accelerograms to simulate the effective seismic demand.

A valid compromise is represented by *Nonlinear Static* (NLS) analysis that, as well as relatively easier than NLD analysis, can provide information about structural response of analyzed building.

Moreover, pushover curves (obtained by NLS analysis) are used to carry out the vulnerability assessment of buildings, following guidelines provided by Eurocode 8, in which is explicit the N2 method [12,13].

Despite its effectiveness, NLS analysis is characterized by several main limitations [7,26,31]. Firstly, using an unimodal profile, proportional to fundamental vibration mode of structure, it does not take into account the effects of higher modes and this can represent a problem for evaluating the correct structural response of irregular buildings. After, an important shortcoming concerns the assumption of time invariant load profiles, which neglect the changes of dynamic parameters of case study (periods, shape of fundamental mode,…) when it reaches the inelastic field.

The problems of structural irregularity, in addition to those above defined, are strongly accentuated with regard to initial hypotheses assumed by engineers that carry out numerical model of building on

* Corresponding author.
E-mail addresses: sergio.ruggieri@poliba.it (S. Ruggieri), francesco.porco@poliba.it (F. Porco), giuseppina.uva@poliba.it (G. Uva).

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which execute subsequent analysis. Involving some structural elements in numerical model, even secondary ones, leads to a variation of structural behavior resultant, which in some cases, can completely change the results of analysis [15,33,35,36].

The focus of this paper is to study the behavior of existing RC buildings, subjected to horizontal actions, when the rigid floor assumption is not valid.

Generally, in the existing buildings, the first task of floor system is transmit gravity loads and it is designed neglecting the ability to transfer to earthquake actions to vertical elements.

An usual hypothesis that practitioners assume is the rigid floor assumption, which is able to reduce both computational effort and *Degree of Freedom* (DoF) of case study. This hypothesis could be incorrect in several cases, as provided by International codes, where the overall configuration of geometric and structural system (dimension of vertical elements, presence of holes of re-entrances in the slab,…) play a fundamental role in the force distribution.

To establish that the floor system is rigid or not, it is important, in the prospective to carry out NLS analysis, where apply the forces or displacements at each level, problem that can add torsional effects to buildings, modifying the resultant pushover curve [43].

The aim of this work is to provide a fast method to practitioner, in order to use the real behavior the floor system, avoiding any hypotheses about this topic.

In particular, a numerical simplified procedure has been proposed, in order to define an equivalent shell thickness of orthotropic material, able to simulate the slab behavior and consequently it allows to exploring the effective in-plane floor deformability.

This procedure is based on numerical results, obtained by a FE micro-modeling carried out with solid elements, used on several models subjected to horizontal actions. The results obtained by linear static analysis on FE micro-models are used to calibrate a slab thickness, through a FE macro-modeling made with shell elements.

The main advantage to define a shell element, rather than using more consolidate methods that simulate the deformability of floor system as “strut model”, is due to the necessity to investigate the in-plane stresses state of elements which constitute slab system, under horizontal actions and, subsequently to carry out the effective verification of ones. Besides, the in-plane stresses distribution can be useful for studying the problem in inelastic field.

In order to verify several cases in which floor system is flexible, the method proposed has been calibrated with a preliminary analysis, considering the variation of several significant parameters, such as dimension of vertical elements, dimension of edge beams, thickness of concrete slab, plane shape ratio and number of floors.

Subsequently, a real case of existing RC buildings has been investigated in elastic field, using a FE micro-modeling and comparing results in terms of modal parameters and base shear, obtained by modal analysis and linear static analysis. Finally, the same results have been compared with ones obtained by same model with proper struts, calculate for each floor, with the aim to evaluate the correctness of method proposed.

2. Study of floor deformability: state of art

In the vulnerability analysis of existing RC building, numerical FE model plays a fundamental role, in which the rigid-floor hypothesis is a common assumption, in order to reduce DoF and computational efforts.

In this regard, the modern codes provide several rules to define if the rigid-floor hypothesis is adequate for RC buildings (new and existing). In particular, each technical law can provide qualitative or quantitative criteria [28].

Regarding to qualitative criteria, codes mainly aim to provide indications on the in-plan shape of diaphragm. In Eurocode 8, the rigid-floor assumption must be verified when buildings have in-plan irregular geometries (as recesses, re-entrances, large opening) or irregular

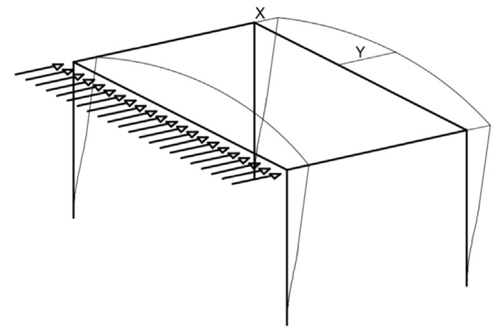

Fig. 1. Deformed shape of structure example, under horizontal actions.

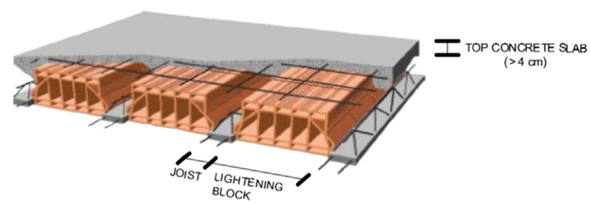

Fig. 2. Example of typical ribbed slab.

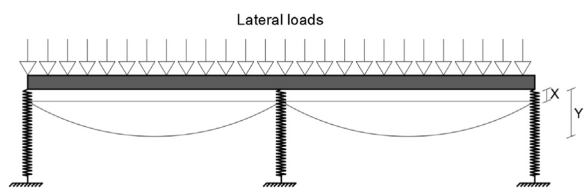

Fig. 3. Beam model.

distribution of mass or stiffness and when buildings are constituted by walls located on the perimeter. For the same codes, usually, in-plane actions effects are estimated through a “deep beam” model (Fig. 3).

Even in NZS 1170.5 [30] in pointed out that the rigid-floor assumption is not valid when there are abrupt discontinuities, major variations in in-plane stiffness and major re-entrant corner in the floor.

In the Greek code [18], it is suggested that the rigid-floor assumption is to avoid when the buildings analyzed have a long shape in plan (length to width ratio > 4), as well as they are constituted by long parts as L, H, U shapes. In these cases, an accurate analysis of lateral force distribution on vertical resistant elements must be carried out, taking into account the weak areas.

Furthermore, in the Eurocode 8 is provided a qualitative criterion related to in-plane displacement under horizontal actions. In particular, it is denoted that the floor must be modeled with its in-plane flexibility when the horizontal displacement exceed more than 10% of those obtained by model with rigid diaphragm.

Concerning to quantitative criteria, codes are focused about the ratio between in-plane maximum and minimum displacements under horizontal actions, like shows in Fig. 1. In particular, a specific limit for this relationship is provided. In this paper, the previous ratio is called “in-plane displacements ratio” and it is indicated like λ, defined as follow:

$$\lambda = Y/X \tag{1}$$

In SEAOC 1999 and ASCE/SEI 7-16 2016 [38,1] is provided a β factor, defined as ratio between maximum lateral deformation of the diaphragm (Δ_{flexible}) and average storey drift of the associated storey (Δ_{storey}). If the ratio is larger than 2, the diaphragm is flexible, vice versa it is rigid. Also in this code, it is suggested that flexible floor can be modeled as a simple beam between vertical resisting elements, whose cross section is constituted by web and flange elements.