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

Original Citation:

A numerical procedure for modeling the floor deformability in seismic analysis of existing RC buildings / Ruggieri, S.; Porco, F.; Uva, G.. - In: JOURNAL OF BUILDING ENGINEERING. - ISSN 2352-7102. - ELETTRONICO. - 19:(2018), pp. 273-284. [10.1016/j.jobe.2018.05.019]

Published version

DOI:10.1016/j.jobe.2018.05.019

Publisher:

A NUMERICAL PROCEDURE FOR MODELLING THE FLOOR DEFORMABILITY IN SEISMIC ANALYSIS OF EXISTING RC BUILDINGS

S. Ruggieri[a], F. Porco[b], G. Uva[c]

KEYWORDS: RC existing buildings, FE model, rigid floor assumption, seismic analysis

ABSTRACT

In this paper, a research study on the behaviour of floor systems in existing *Reinforced Concrete* (RC) buildings under horizontal actions is presented. Generally, vulnerability analysis consists of studying the effective structural behaviour of buildings, in order to carry out an assessment, comparing seismic demand and structural capacity. To this purpose, the hypothesis at the base of *Finite Element* (FE) numerical models, the rigid floor assumption, assumes a primary role for the accuracy of seismic analysis results.

In this study, after carrying out a preliminary assessment on the significant parameters that influence floor stiffness, a new simplified numerical procedure has been proposed. Starting with micro-models made of solid elements for several simple applications, the behaviour of a floor system in the elastic field has been analyzed in terms of in-plane displacements and the thickness of an equivalent shell of orthotropic material has been defined, usable in a 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 slab flexibility is simulated with a more consolidated method like a "strut model".

The numerical analyses have enabled interesting indications to be given about both the accuracy of a rigid floor assumption and the 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 (Eurocode 8 1994) and consequently some national codes, 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 (Fajfar and Gasperic 1996, Fajfar 2000). Despite its effectiveness, NLS analysis is characterized by several main limitations (Krawinkler and Seneviratna 2000, Chopra and Goel 2001, Papanikolau et al. 2005). 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 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 (Porco et al. 2013a, Porco et al. 2013b, Fiore at al. 2013, Ruggieri at al. 2017).

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 (Uva et al. 2017).

The aim of this work is to provide a fast method to practitioner, in order to use the real behaviour 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.

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 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 (Figure 3).

Even in NZS 1170.5 (New Zeland Standards 1170.5 2004) 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 (Greek Seismic Code 2000), 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 Figure 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:

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

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

In SEAOC 1999 and ASCE/SEI 7-16 2016 (Structural Engineers Association of California 1999, American Society of Civil Engineers 20016) is provided a β factor, defined as ratio between maximum lateral deformation of the diaphragm ($\Delta_{flexible}$) 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.

Even in IBC 2009 (International Building Code 2009) is defined the same factor β, as soon as the previous code.

In the Iranian Code (Iranian Code standard 2007) another factor is defined, called λ, obtained by ratio between the maximum lateral deformation of the diaphragm along its length (Δ_{flex}) and the inter-storey drift evaluated on the considered storey and the immediately below one (Δ_{stor}). If this ratio is smaller than 0.5, the diaphragm is rigid, vice versa it is flexible.

In FEMA 2012 (Federal Emergency Management Agency 2012) is defined the same factor of previous code, but ascertaining the diaphragm as rigid when λ is larger than 2. When this value is included between 0.5 and 2, the diaphragm is defined as stiff and it should be modeled with its stiffness. For concrete diaphragm, the model suggested is a continuous elastic beam supported by elements of varying stiffness.

Regarding to the construction details of RC slab, in the Eurocode 8 is defined that the thickness of concrete slab must be larger than 80 mm and the thickness of top concrete slab (concrete part over joists), as showed in Figure 2 (typical of RC existing buildings), must be larger than 40 mm.

Fig. 2 – Example of typical ribbed slab

In the recent years, the scientific community has strongly improved the background on RC buildings structural behavior under horizontal action as seismic loads, evaluating the effects of flexible floor.

Already from the more ancient study, a lot of researchers show best highlights of this focus and with the growing of the computational tools, several applications have been carried out.

Firstly, Goldberg (1967) showed that the rigid-floor assumption in RC buildings is less and less valid when the ratio between vertical elements stiffness and in-plane elements stiffness increases (in this paper defined as "relative stiffness ratio").

In another research, Blume et al. (1961), analyzing the dynamic behavior of existing RC school buildings, did not focus on in-plane flexibility of floors but showed the possible structural damage under seismic actions, especially for the structures having RC walls.

Subsequently, several authors (Nakashima 1982, Jain 1984, Jain and Jennings 1985, Aktan and Nelson 1988) quantified the error committed using the rigid floor assumption and its limits, through various simple models in which the floor was schematized by continuous beams, which considers both shear and flexural deformation.

Saffarini and Qudaimat (1992) analyzed several RC buildings for comparing the difference between rigid floor and flexible-floor. A sensitivity analysis was carried out, through numerical models where some parameters were varied, such as number of stories, story height, slab type, building-plan aspect ratio, regularity of building plan, openings in the slab, the sizes and spacing of columns and shear walls. They found that the rigid-floor assumption is accurate for buildings without shear walls, but it can cause errors for building systems with shear walls. This error was quantified through a stiffness factor R_i which depended by relative stiffness ratio. In the same work was ensured how in-plane irregularity, given by strong recesses and large opening in the slab, can cause the deformability of floor.

Ju and Lin (1999) quantified the error of rigid floor assumption, analyzing several RC frames and walls buildings. They believed the aforementioned hypothesis was valid if the in-plane displacement was not smaller than 20% of the same displacement obtained by deformable floor. When this difference exceed of 45%, the error in the stress distribution became significant, about 40%.

A consequence of different stress distribution in the vertical elements, due to floor deformability, is the reduction of torsional coupling, which can be a positive aspect for RC buildings.

Kunnath et al. (1991) studied the effect of deformable floor system on regular frame building with shear walls on the structure sides, using a simplified macro-modeling scheme, which included an inelastic behavior. The authors show that, using the two different hypotheses about the floor stiffness, the shear distribution among columns and shear walls change. In this case, the design of the building with shear wall can be not conservative if one consider the rigid floor assumption, because in the inelastic field the internal frames need larger strength and ductility demand. This evidence increase the possibility of columns mechanisms.

Dolce et al., (1994) studied the inelastic dynamic response of a large number of simple models, which simulate the floor system. On their cases studied, they analyzed the variability of the ratio k_{floor}/k_{vert}, using a spring model and varying the elements stiffness. They obtained that, when the stiffness distribution of structural vertical elements was uniform, the flexibility of floor system was negligible, while when the structures had important re-entrances, the deformability effect was relevant.

In Tena-Colunga (1992) and Tena-Colunga and Abrams (1995) an existing buildings was monitored, measuring its response during the Loma Prieta Earthquake, and subsequently it was modeled using firstly a simple model and after a more complex FE model. In addition, it was evaluated the difference obtained in the rigid floor assumption or not (Tena-Colunga and Abrams (1996)).

Following, other authors studied aspects related to in-plan irregularity effects and dynamic parameters of buildings analyzed (periods, participating mass), through different modeling methods and using the hypothesis of rigid floor or not (Fleishman and Farrow 2002, Fleishman et.al 2001, Lee at al. 2002; Fouad at al. 2012; Bakar et al. 2014; Khajehdehi and Panahshahi 2016, Barron and Hueste 2004).

In some works, it was analyzed the structural behavior of RC existing building, varying the typology and constituent elements of slab. In particular, Tena-Colunga et al. (2015) studied the effects of different slab typology and its thickness on several type of buildings.

In Pecce et al. (2017), a research of lightening elements role in the slab was carried out and authors, using elastic solid models of slabs, authors determined an equivalent slab thickness, made of a homogenous concrete layer.

In conclusion, the effects of in plane deformability can not be neglected a priori, especially when the aim of analysis is the vulnerability assessment of existing RC buildings. From this point of view, the cases of major interest can be when the thickness of top concrete slab is smaller than 4 cm or when in a retrofit solution, in which the dimensions of vertical resistant elements are increased, the rigid floor assumption can be back out.

3. PROPOSAL OF NEW NUMERICAL PROCEDURE

A correct numerical model of floor system in RC buildings, which simulates the real structural response, must be composed by an in-plane FE, which can be both rigid and deformable, depending by several boundary conditions. As showed in the previous section, floor system performance has a strong dependence by in-plane displacements caused by horizontal actions.

Generally, the diaphragm is rigid when the ratio between maximum and minimum displacements is “low” and it is deformable when the same ratio is “high” (in International seismic codes, the limit of this ratio is equal 2). In the first case, to simulate this condition, engineers can use an internal constraint in the floor, in order to concentrate the mass in the geometric center and to reduce the computational effort of any analyses. In the second case, the equality of floor points displacements can not be ensured. In this situation, users can resort to several methodologies, even simplified, in order to find the correct in-plane displacement and, consequently, the correct stress distribution and modal parameters.

To these scopes, the first typology of model developed was the “beam model”, showed in Figure 3. In this *bi-dimensional* (2D) model, the bays of floor are schematized as a continuous beam and each vertical elements are represented by elastic supports with their stiffness. The maximum displacement is provided by the deflection in the center of each bays (Y) and the minimum displacement is the deflection of supports (X).

Fig.3 – Beam model

Another more refined model typology developed, is the “strut model”, showed in Figure 4. In this *three-dimensional* (3D) model, the floor system is schematized by 2 cross equivalent struts with dimensions of section computed equaling slab stiffness (K_{slab}) and equivalent strut stiffness (K_{strut}).

Slab stiffness is defined as follow:

$$K_{slab} = \frac{1}{\frac{L'^3}{12\,J\,E_C}+\frac{L'}{A_S G_C}} \tag{2}$$

where L’ is the slab dimension orthogonal to seismic action, J is the inertia moment of slab section, A_s is the shear area of section slab, E_c is the elastic modulus of slab material, G_c is the shear modulus of slab material, while:

$$K_{strut} = \frac{E_s A_S}{L_S} \tag{3}$$

where E_s is the elastic modulus of strut material, L_s is the length of strut and A_s is the area of section strut, that is the only unconscious term of equation.

Fig.4 – Strut model

In addition to aforementioned modeling procedures, scientific community has developed other elastic and inelastic modeling methods, using a membrane element, like equivalent shell or solid models. The main advantage of these models is the property to compute the in-plane stresses state of slab, which allows to carry out its local verify.

For assessing the floor deformability under horizontal actions of RC buildings and for studying the in-plane displacements of floor system, a new simplified procedure has been proposed, which leads to have a correct shell thickness.

The new numerical procedure is summarized as follow and it is graphically outlined in flow chart in Figure 5:

- For each "floor field", defined as the part of floor encloses among minimum 4 beams (two in one way and two in the other way) and below columns, a FE micro-model, using solid elements, is carried out;
- In each analyzed model, loaded with a fixed horizontal action, the maximum and minimum in-plane displacements are detected and the ratio between them is computed (in this paper "in-plane displacement ratio");
- For each application, an equivalent FE macro-model is carried out. In particular, beams and columns are modeled with frame elements, while slab is modeled with shell elements.
- Using in-plane displacement ratio, previously determined, shell thickness is calibrated. Assigning to trial a shell thickness value, the macro-model must have the same in-plane displacement ratio of micro-model;
- If the differences between solid and frame models is greater than 10%, the shell thickness assigned must be changes.

The procedure application are showed in next paragraphs, firstly analyzing simple cases, in which several significant parameters are varied and secondly, on a real case study.

3.1 FE SOLID MODELS: MICRO-MODELLING

The floor system typology considered is a RC ribbed slab, where the RC joists have constant dimension (height 20 cm, width 10 cm, spaced 50 cm) and the lightening blocks contribute is neglected (despite it is an important aspect, as show in Pecce 2017). The thickness of top concrete slab can be varied from 5 cm to 1 cm, in order to emulate floor system of some real cases of existing RC buildings, which have a top concrete slabs with null (SAP slab) or low thickness. This latter condition is caused by the presence in the floor system of hydraulic and electrical systems or human mistakes.

Micro-model is based on a reference 3D model, which has dimension of 100 cm x 100 cm. It is modeled using SAP2000 software (SAP2000 2016) as shown in Figure 6. The 3D reference model is implemented through solid elements (FE with a minimum eight nodes, which take into account the bending and the shear deformation), whose height is 1 cm for modeling the thickness of the top concrete slab with the right dimension. The in-plane dimensions of elements are in the order of centimeter, for avoiding locking problems. Each model is developed to assess in-plane displacements ratio and for this reason, every models are elastic. The mesh chosen is fixed, assuring a maximum scatter of 3% in results, respect to a fitter mesh or same model with square elements.

Material of reference 3D model can be fixed according with the needs of user. In cases analyzed, mechanical parameters of concrete chosen are defined according to class C25/30, as classified in Eurocode 8. Cubic compressive strength of 30 MPa, elastic modulus (E) is 31467 MPa, shear modulus (G) is 11315 MPa and Poisson's ratio (ν) is equal to 0,2.

Generally, each application is constituted by one or two bays in both directions and height fixed to 300 cm.

To this scope, micro-models are made duplicating the reference 3D model. Edge beams, which have dimension fixed to 30 cm x 30 cm, enclose the entire chosen extension of slab and they are modeled with mesh in accordance to the dimension of slab mesh elements. For reducing computational efforts of analysis, vertical resistant elements are modeled with frame or shell elements. Their main aim is just to modify vertical stiffness, and thus the relative stiffness ratio.

Furthermore, when models have more storeys, frame elements are connected with linear link, ensuring an equal displacement of the elements, which converge in the node.

Fig. 5 – Summary of new procedure proposed

To simulate horizontal actions, an uniform load equal to 1 KN/m^2 is applied on the solid surface of edge beams, on each model.

Fig. 6 – Reference 3D solid model (1 mt x 1 mt), with top concrete slab of 5 cm

Regarding to the preliminary analyses carried out, thickness of top concrete slab is ever varied from 5 cm to 1 cm, removing 1 cm each time. Vertical resistant elements are columns and walls and their dimension are varied as shown in Table 1:

Tab. 1 – Variation of vertical elements dimensions

Moreover, some parameters, which modify in significant way the results in terms of in-plane displacement ratio, are varied, considering that each model represents a floor field, as follow:

- In-plane shape ratio – 1:2, 1:3, 1:4, with 1 length equal to 300 cm;
- Number of storeys – 1, 3, 5;
- Loads applied in both orthogonal and parallel to joists directions.

For each case analyzed in the above list, the geometric and mechanic features of slabs, beams and columns or walls are changed one by one. Then, the results of analyses carried out on FE micro-model are summarized and, some of these are shown in Porco et al. (2017). In particular, in this paper authors carried out a sensitivity analysis, base of the work shows in this document. Starting from a reference models with rigid and deformable floor system and varying some geometrical parameters (number of storeys, in-plane shaper ratio), the differences in terms of in-plane displacement ratio, under horizontal actions, had been showed. In addition, 2 simple numerical applications has been carried out, through a FE solid modeling, in order to assess the influence of walls (perimeter and C-shape) on the floor flexibility.

Figure 7 shows some examples of micro-models.

Fig. 7 – Micro-models with parameters variation

It is important to specify that the choices of the minimum dimensions of the reference model and the successive sensitivity analysis have been done according to observation on real R.C. (residential and school) existing buildings (or part of them) in the South Italy.

The application of horizontal loads on models has showed results similar to what provided by scientific literature, in terms of displacements. In each model analyzed, the in-plane displacement ratio is evaluated. For the models with more levels, the value of in-plane displacement ratio takes into account is the one at the first level, considering that on the upper storeys, this value is always lower.

Generally, minimum in-plane displacement is strongly dependent by vertical elements stiffness, while maximum in-plane displacement is strongly dependent by in-plane elements stiffness.

Relying on the in-plane displacement ratio results, the floor system is more flexible when vertical elements dimensions are larger and the thickness of top concrete slab is smaller.

At the same conditions of vertical elements dimensions and thickness of top concrete slab, floor system is more flexible when the in-plane shape ratio increases and it is less flexible when the number of storeys increases.

From the point of view of loads, floor system is more flexible when the loads act perpendicularly of joists direction. In fact, in this case, the bending stiffness of joists has a little influence on in-plane displacement, while in the opposite case, the in-plane displacement ratio is smaller than the previous one, because the axial stiffness of joists participates to reduce the maximum in-plane displacement.

3.2 EQUIVALENT SHELL THICKNESS: MACRO-MODELLING

Using the results obtained by micro-models, it is possible to define an equivalent shell (FE with four nodes) that simulates a homogenous concrete slab with unitary thickness with same behavior of the aforementioned model. The numerical element used for modeling the floor system is like “shell thick” which simulate the behavior of a thick-plate. This kind of FE is based on the Mindlin/Reissner formulation in which it is included the transverse shearing deformation.

In SAP2000 software, same applications have been modeled as macro-models, with same horizontal load and boundary conditions. In particular, edge beams dimensions are modeled through frame elements with fixed dimension of 30 cm x 30 cm (according to the dimensions used for the micro-models), vertical element dimensions vary as in Table 1. Shell elements are meshed using square FE having dimensions of 50 cm. Assigning to trial a value of shell thickness, it is gradually varied, in order to obtain the same in-plane displacement ratio of micro-models, with a maximum error of 10% (in absolute value).

Using this methodology, for the cases performed in preliminary analysis, a summary of equivalent shell thickness is presented in the graphs in Figure 8, which have in abscissa the “inertia moment of vertical elements” and in ordinate the thickness.

The inertia moment of vertical element is the sum of inertia moments of each vertical structural element under the structure considered. The choice of this parameter is due to the strong importance of relative stiffness between vertical and horizontal elements.

Each graph shows 3 curves, where each curve is representative of one in-plane shape. Difference between graphs is due to loading direction, with regard to joists warping and they are defined considering both top concrete slab thickness and loading direction fixed. In particular, in the graphs, each stars points out the value of equivalent shell for a model with dimension of vertical element shown in Table 1. For clarity of image, the points of the models with columns of 40 cm and 50 cm are not depicted in the graphs. Furthermore, the figure takes into account the models with more levels, considering the value of in-plane displacement ratio at first level, in a conservative way.

For same model, a practitioner can enter into the two graphs with same inertia and obtain the equivalent shell thicknesses resultant.

Whereas the thicknesses in output are different for the two directions, but in numerical model the slab must be only one, practitioner can assume the smallest shell thickness (usually the dimension obtained loading orthogonally to slab warping) and change the elastic properties of material in the other direction.

Then, using the relationship 4, an orthotropic concrete material is defined. In particular, in direction where thickness is higher, a higher value of modulus E (and consequently G) is determined, maintaining the shell thickness constant (lower value). The equation 4 is show as follow:

$$E_p = \frac{h_p}{h_o} E_o \tag{4}$$

where "o" and "p" point respectively orthogonal and parallel. The terms in eq. 4 are the parameters that describe the in-plane stiffness of slab and, in this way, the in-plane deformability of slab in both directions is insured, coherently to what obtained by FE micro-model results.

Fig. 8 – Graphs defined through preliminary analysis, to determine equivalent shell thickness (fixed top concrete slab produce equal to 4 cm; loading orthogonal and parallel)

In the Figure 8, in some cases, the thickness of equivalent shell can be lower than the real thickness of top concrete slab. For this method, which is a numerical method, this evidence can be acceptable because, as just widely shown, the value of shell thickness is strongly dependent by the dimension of vertical elements, according to FE micro-model results.

4. APPLICATION OF PROCEDURE: A CASE STUDY

In order to verify the new simplified procedure to define an equivalent shell thickness, an existing RC building is analyzed. The case study is an existing RC school building located in Castelluccio Valmaggiore (Province of Foggia, Puglia, Southern Italy), which has a plant inscribed in a rectangle of dimension 20.00 m x 27.85 m, 3 floors above ground and a pitched roof with total height of 14.00 m, as shows in Figure 9.

Fig.9 – Orthophoto of case study

The structure, built in the 60s' in the absence of specific seismic codes, was designed considering only vertical loads and it is constituted by a R.C. frame with beams and columns.

Following the investigation performed within an Agreement between AdB Puglia and Polytechnic University of Bari, in which vulnerability analyses on school buildings in the Province of Foggia are carried out, in order to develop "Guidelines for the vulnerability assessment of existing buildings".

Dimensions of the structural elements, design loads and mechanical parameters of materials (determined through in-situ investigation on concrete elements and steel rebar's) are summarized in Table 2, where B and H are the dimensions of beams and columns, f'_{cm} and f'_{ym} are respectively the in-situ compressive strength of concrete and steel rebar, G_1 and G_2 are the gravity permanent loads, Q is the live loads and Q_s is the snow load.

The foundations are constituted by plinths connected by beams, while the warping of elevation beams is in just one way. Staircase is modeled considering its influence, in terms of masses, on competence beams.

Tab.2 - Dimensions of the structural elements, design loads and mechanical parameters of materials

The slab typology of building is a RC ribbed slab, with constant joists dimensions (height 20 cm, width 10 cm, spaced 50 cm) and thickness of top concrete slab of 4 cm.

4.1 NUMERICAL MODELLING

The structural modeling of the case study is performed by using the FE software SAP2000. Beams and columns are modeled as one-dimensional frame elements, assuming fixed-end restraints at the base of the columns. On each floor, horizontal joint forces of 1 kN (it is not important the value of the forces, because the analysis will be linear) are applied in one direction (weak axis), in order to simulate a constant load profile over the height of building.

The numerical model has been duplicated, in order to consider and not the rigid floor assumption. In fact, in one model, an internal rigid diaphragm constraint at each floor has been inserted, while in other model, through the procedure described in the previous section, shell elements have been defined and inserted. Shell elements, which simulate the slab, are meshed in square elements with dimension of 50 cm, coherently with shell mesh of macro-models.

Frames, directly linked to shell, have been meshed coherently with slab mesh, for obtaining the correspondence of each joint.

To calculate the thickness of equivalent slab, the first operation is determine the in-plane shape ratio of each floor field including among beams, as showed in Figure 10.

Fig. 10 – Typical floor configuration with indication of each floor field

Considering that the floor fields identified regard the cases already analyzed in preliminary analysis, it is possible to apply the procedure using graphs in Figure 8.

Choosing the curve corresponding to in-plane shape ratio and considering the inertia of vertical elements under each floor part, two thicknesses of equivalent shell can be defined, for loading parallel and orthogonal to joists warping. The results of the application of procedure is summarized in Table 3.

Subsequently, the thickness detected in the direction orthogonal to joists warping is assumed as equivalent shell thickness, while other thickness is used to define different elastic parameters of materials (E, G) in the other direction, according to Equation 4.

Tab.3 – Value of thicknesses of floor fields and modified elastic parameters

Comparison between models defined, with rigid floor assumption and not, are showed in the Table 4, in terms of modal parameters as fundamental period (T) and participating mass in direction X and Y (M^*_x and M^*_y) and rotational mass (M_θ).

Tab.4 – Comparison between models with rigid floor assumption and not

The low differences (in the order of 10%) between models show that, in this case, rigid floor assumption is an appropriate hypothesis. Furthermore, even stress distribution over both vertical and horizontal structural element is similar in both models.

Clearly, using this shell element, the hypothesis of rigid floor can be avoid. The comparison with rigid floor model has been done for demonstrating that the shell element can be used in each case.

4.2 SIMULATION OF A RETROFIT SOLUTION

In order to clarify the role of a possible retrofit solution effect on structural response, from the point of view of floor flexibility, considering the irregular dynamic behavior of building study, it is hypothesized to insert RC walls of 40 cm to the both small edges of building, over horizontal loading direction (weak direction). It is important to clarify that the addition of 2 shear walls is one of possible retrofit solutions, which emphasize the behavior of floor system. This choice is usual among practitioners, which have the aim to regularize the dynamic behavior of existing structure and to increase the strength of the one.

Also in this case, two models are realized considering and not the rigid floor assumption. RC walls are modeled as shell elements meshed coherently with slab and frame mesh, for obtaining the correspondence of each joint. The numerical element used for modeling the floor system is like “shell thick”, the same used for modeling the floor system. This choice is coherent with the modeling way of the sensitivity analyses. In Figure 11 two models with RC walls added are showed.

Fig. 11 – Models with RC walls

The variation of vertical element dimensions, leads that the equivalent shell thickness in same floor part must be recalculated, following the same procedure abovementioned.

In terms of modal analysis, comparison of results, Table 5 show that, already from the fundamentals period, the difference are not negligible. In particular, the model with flexible floor has a period higher than another one.

In the same way to the previous models, the value of the fundamental vibration mode is shown. In this case, the inclusion of walls in the models cause the inversion of fundamental vibration mode direction (in long direction).

Tab.5 – Comparison between models, with RC walls, with rigid floor assumption and not

Furthermore, it is displayed the in-plane deformed shape of building with RC walls, with rigid floor assumption and not, under the same loading of the previous model. The structural behaviour results strongly different, cause the two different hypothesis made on floor system.
In Figure 12 is shown that the floor system, in the model with slab made by shell elements, has a deformed shape at each level similar to the one obtained by a support beam under uniformly distributed load.

Fig. 12 – Comparison of in-plane deformed shape between models, with RC walls, with rigid floor assumption and not

In addition, stress distribution on structural elements, derived by the same static analysis, is different between two models and, in particular, the percentage differences in terms of base shear distribution between walls and columns, under rigid floor assumption and not, are shown in Table 6.

Tab.6 – Differences stresses states between models, expressed in terms of total base shear percentage.

Supposedly, rigid floor assumption is not accurate in this case. In order to verify the reliability of method adopted, same building with RC walls is modeled using "strut model", mentioned in section 3.
Since all floor parts are not square (necessary request for applying the strut model method), each one has been divided into square portion and following the relationships (2) and (3), areas of struts are calculated (similar for all levels). Assuming the struts section as square, dimension are calculated through square root of areas founded. In Table 7 is summarized the dimensions of struts section for all floor field, numerated as in previous application. In Figure 13, the case study modeled with struts on each floor is showed.

Tab.7 – Dimension of struts

Fig. 13 – Strut model on case study

In Table 8, the values of modal parameters are shown for the fundamental vibration mode and in this case, as foreseeable, the models are similar (with percentage differences in order of 10%).

Tab.8 – Comparison between models, with RC walls and slab modeled using both shell and struts

The in-plan deformed shape (Figure 14) of strut model is strongly similar to one obtained by model with equivalent shell. The only difference between the model proposed and strut model is due to the possibility to display the distribution of in-plane stress states, which does not match using struts. The main advantage is that, using a computational source with low effort, is possible to carry out local and global assessment of top concrete slab and joists.
Furthermore, they are greatly different from results obtained by model with rigid floor assumption.

Fig. 14 – In-plane deformed shape of strut model

Tab.9 – Comparison between strut model and equivalent shell model, in terms of modal parameters and base shear

In Figure 15, the in-plane stresses state of a floor system of the case study is shown. Near to the Figure, it is provides a grey scale with both tensile state of light colour and compression states of dark colour. The values attached to the grey scale are provided basing on the horizontal forces applied with values above provided.

Fig. 15 – In-plane stresses state of existing building analyzed

In the case of linear analysis, the method can give different values, basing on the force distribution assumed.
Furthermore, in the case of retrofit solution, authors avoided to indicate if the plane is rigid or deformable according to International seismic code, because quantitative and qualitative criteria described in Section 2 lose their meaning without the assumption about the floor system stiffness.

5. CONCLUSIONS

In the present paper, the behaviour of floor system in existing RC buildings under horizontal actions is investigated, assessing the rigid floor assumption.

Usually, in the existing buildings, the floor system is designed only for transmit gravity loads to vertical elements and to assign the hypothesis of rigid floor could be not conservative.

As shown in several research paper, in the cases in which the hypothesis is not valid, results of linear and nonlinear analysis (as NLS), in terms of base shear distribution, stresses states of structural elements, displacement, deformed shape, modal parameters, can not be accurate.

For this reason, a numerical simplified procedure has been proposed, able to provide a method to simulate the real behavior of floor system, in elastic field.

To this purpose, after providing the international codes indications to define the stiffness of floor, in a preliminary analysis, rigid floor assumption is investigated for defining the significant parameters: slab typology, vertical elements stiffness, geometry (in-plane shape ratio, number of storeys) and loading direction.

Preliminary analysis aforementioned is carried out varying these parameters on several models, which simulate floor fields (defined as part of floor enclosed among minimum 4 beams, two in one way and two in the other way, and the below columns) in real cases of existing buildings. Here, the slab warping is in one way and the in-plane shape rarely exceed a ratio equal to 1:4.

On the basis of the results obtained by micro-models, made with solid elements on cases of preliminary analysis, in terms of in-plane displacement ratio (defined as ratio between maximum and minimum in-plane displacement under an horizontal action fixed), an equivalent shell thickness of orthotropic material are calibrated, in order to define macro-models, able to explore the effective in-plane floor deformability.

Summary of results of procedure is set out in particular graphs, which relate the thickness of equivalent shell and the sum of inertia moments of vertical elements under floor field taken into account. This representation has been useful to quickly implement the procedure on a real existing RC building.

The case study, well defined in terms of geometry, materials and loads, is studied developing two FE models, firstly using the rigid floor assumption and secondly, simulating the slab system with equivalent shells of orthotropic material. Carrying out a modal linear analysis on both models, results in terms of dynamic parameters has shown a substantial equivalence between models, demonstrating that the shell element proposed is usable even when the rigid floor assumption is valid.

Subsequently, simulating a retrofit solution through insertion of RC walls at edges of building, same models aforementioned are performed and, results of modal analysis, proving that the rigid floor assumption is not valid and provides great differences. In particular, fundamental period of buildings, using the rigid floor assumption, is lower than the one obtained using equivalent shell. The in-plane deformed shape obtained with a static linear analysis shows that the base shear distribution among vertical elements (columns and walls) results quite different. In fact, in the model with rigid floor assumption, base shear is almost completely assigned to RC walls while, in the model with equivalent shell, a larger part of base shear is assigned to frame system, as confirmed in the scientific literature.

In order to assess the procedure proposed, model with equivalent shell has been compared with same model in which the slab behaviour is simulated by using proper calculate struts. The comparison of models has showed a good convergence of results in terms of modal parameters and base shear on frame system and RC walls.

The main advantage to define an equivalent shell, compared to a more consolidate methods for simulate the slab behavior as “strut model”, is exactly the characterization of the in-plane stresses state of slab system, under horizontal actions, useful for the structural verification of elements which constitute the slab. Furthermore, using this method, the hypothesis on floor system stiffness can be avoid, especially in the retrofit cases where it is usual to increase the dimension of vertical elements or their stiffness through reinforced material (as fiber reinforced plastic).

The future aim of this research is calibrates the nonlinear behavior of equivalent shell, using the results in terms of in-plane distribution, in order to carry out the NLS and NLD analyses.

6. REFERENCES

- American Society of Civil Engineers (2002) Minimum Design Loads and Associated Criteria for Buildings and Other Structures American Society of Civil Engineers ASCE/SEI 7-16. 2017
- Aktan A.E., Nelson G.E. (1988) Problems in predicting seismic responses of RC buildings. J Struct Eng ASCE 114(9):2036
- Ahmadi M., Bakar S. A., Abbas H. S., Investigation into diaphragm flexibility using shear wall. Journal of the Croatian Association of Civil Engineers - Građevinar, 66(9), 831-836, 2014. doi: 10.14256/JCE.1049.2014
- Barron JM, Hueste MBD (2004) Diaphragm effects in rectangular reinforced concrete buildings. ACI Struct J 101(5):615–624
- Blume J.A., Sharpe R.L., Elsesser E. (1961) A structural dynamic investigation of fifteen school buildings subjected to simulated earthquake motion. Division of Agriculture, Sacramento

- Circolare n. 617 del 2/2/2009 - Ministero delle Infrastrutture e dei Trasporti. Istruzioni per l'applicazione delle "Norme tecniche per le Costruzioni" di cui al D.M. 14/01/2008. G.U. n. 47 del 26/2/09 suppl. ord. n. 27
- Chopra A., Goel R., Chintanapakdee C., Statistics of SDF-System Estimate of Roof Displacement for Pushover Analysis of Buildings, Pacific Earthquake Engineering Research Center, PEER 2001/16, December 2001.
- Computer and Structures I. SAP2000, Advanced 18. Structural Analysis Program– Manual – Computer and Structures, Inc, Berkeley, California, USA, 2016.
- DM 14/01/2008, Norme Tecniche per le Costruzioni. Gazzetta Ufficiale n. 29. Rome2008.
- Dolce M., Lorusso V.D., Masi A., Seismic response of building structures with flexible inelastic diaphragm. The structural design of tall buildings, 3, 87- 106, 1994. DOI: 10.1002/(SICI)1099-1794(199706)6:2
- Eurocode 8 (1994) Earthquake resistant design of structures. Part I: General rules and rules for buildings. Eur. Prestandard prENV 1988-1-1:1994, European Committee for Standardization (CEN) Brussels Belgium
- Fajfar P. A Nonlinear Analysis Method for Performance-Based Seismic Design. Earthquake Spectra. 2000;16:573-92. https://doi.org/10.1193/1.1586128
- Fajfar P., Gaspersic P. The N2 method for the seismic damage analysis of RC buildings. Earthquake Engineering & Structural Dynamics 1996; 25(1):31– 46. DOI: 10.1002/(SICI)1096-9845(199601)25:1
- FEMA 2012 *Seismic Performance Assessment of Buildings Report No. P58-1, Volume 1 Methodology*, p. 319. FEMA, Prepared by Applied Technology Council (ATC), Redwood City, CA, USA
- Fiore A., Porco F., Uva G., Mezzina M., On the dispersion of data collected by in situ diagnostic of the existing concrete. Construction and Building Materials, 2013, 47, pp. 208-217. https://doi.org/10.1016/j.conbuildmat.2013.05.001
- Fleischman R. B., Farrow K. T., Dynamic behaviour of perimeter lateral-system structures with flexible diaphragms. Earthquake engineering and structural dynamics, 30, 745–763, 2001. doi: 10.1002/eqe.3
- Fouad K., Ali Z., Mustapha R., Structural Analyses with Flexibility Effect of the Floor Slabs. 15 World Conference on Earthquake Engineering, Lisbon, 2012.
- Greek Seismic Code (2000) Earthquake resistant design of structures. Earthquake Planning and Protection Organization, Athens
- Goldberg J.E. (1967) Analysis of multi-story buildings considering shear wall and floor deformations Tall buildings. Pergamon Press Long, Island City, pp 349–373
- International Building Code (IBC) (2009) International Code Council, Country Club Hills
- Iranian -Code of Practice for Seismic Resistant Design of Buildings (2007) Standard no 2800-05 3rd Edition
- Jain S.K., Jennings P.C. (1985) Analytical models for low-rise buildings with flexible floor diaphragms. Earthq Eng Struct Dyn 13:225–241. DOI: 10.1002/eqe.4290130207
- Jain S.K. (1984) Seismic response of buildings with flexible floors. J Eng Mech ASCE 110(1):125–129. https://doi.org/10.1061/(ASCE)0733-9399(1984)110:1(125)
- Ju S. H., Lin M. C., Comparison of building analyses assuming rigid or flexible floor. J Struct Eng ASCE 125:25–39. https://doi.org/10.1061/(ASCE)0733-9445(2000)126:2(273)
- Khajehdehi R., Panahshahi N. (2016) Effect of openings on in-plane structural behaviour of reinforced concrete floor slabs. J Build Eng 7:1–11
- Krawinkler H., Seneviratna G. D. P. K., Pros and cons of pushover analysis for seismic performance evaluation, Engrg. Struct., 1998; 20(4 – 6):452– 464. DOI: 10.1016/S0141-0296(97)00092-8
- Kunnath S. K., Panahshahi N., Reinhorn A. M., Seismic response of RC buildings with inelastic floor diaphragms. Journal of Structural Engineering ASCE, 117(4), 1218-1237, 1991. ISSN 0733-9445.
- Moeni M., Rafezy. B., Investigation into the Floor Diaphragms Flexibility in Reinforced Concrete Structures and Code Provision. Global Journal of Researches in Engineering, 11(1), 25-35, 2011. ISSN: 0975-5861.
- Nakashima M., Huang T., Lu L.W. (1982) Experimental study of beam-supported slabs under in-plane loading. ACI Struct J 79(1):59–65
- New Zealand Standard (NZS) 1170.5 Supp 1:2004 (2004) Structural Design Actions. Part 5: Earthquake actions New Zealand—Commentary, Standards New Zealand, Wellington
- Papanikolau V. K., Elnashai A.S., Pareja J. F., Limits of applicability of Conventional and Adaptive Pushover Analysis for Seismic Response Assessment, Mid-America Eartquake Center, Civil and Environmental Engineering Department, University of Illinois at Urbana-Champaign, March 2005.
- Pecce, M., Ceroni, F., Maddaloni, G. et al., Assessment of the in-plane deformability of RC floors with traditional and innovative lightening elements in RC framed and wall structures, Bull Earthquake Eng (2017). doi:10.1007/s10518-017-0083-0
- Porco F., Porco G., Uva G., Sangirardi, M., Experimental characterization of "non-engineered" masonry systems in a highly seismic prone area. Construction and Building Materials 2013a, 48, pp. 406-416. https://doi.org/10.1016/j.conbuildmat.2013.07.028
- Porco F., Ruggieri S., Raffaele D., Influence of rigid floor assumption in seismic analysis of RC existing buildings. COMPDYN 2017 - 6h ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering. Rhodes Island, 15-18/6, in press.

- Porco F., Uva G., Sangirardi M., Casolo S., About the reliability of punching verifications in reinforced concrete flat slabs. Open Construction and Building Technology Journal 2013b, 7, pp. 74-87. doi: 10.2174/1874836801307010074
- Ruggieri S., Porco F., Raffaele D., Uva G., Rigid floor assumption in nonlinear static analysis of reinforced concrete existing buildings. XVII convegno Anidis. Pistoia, 2017, sa17-21/9, in press.
- Saffarini H., Qudaimat M., In-plan e floor deformations in RC structures. Journal of Structural Engineering, 118(11), 3089- 3102, 1992. ISSN 0733-9445.Structural Engineering ASCE, 125, 25-39, 1999. http://dx.doi.org/10.1061.
- Structural Engineers Association of California (SEAOC) (1999) Recommended Lateral Force Requirements and Commentary, Seismology Committee Structural Engineers Association of California, Seventh Edition, Sacramento, California
- Tena-Colunga, A., "Seismic evaluation of unreinforced masonry structures with flexible diaphragms", Earthquake Spectra, 1992, Vol. 8, No. 2, pp. 305-318.
- Tena-Colunga A., Chinchilla-Portillo K.L., Juarez-Luna G., Assessment of the diaphragm condition for floor systems used in urban buildings. Engineering Structures, 93, 70–84, 2015. http://dx.doi.org/10.1016/j.engstruct.2015.03.025
- Tena-Colunga, A. and D. P. Abrams, "Simplified 3-D dynamic analysis of structures with flexible diaphragms", Earthquake Engineering & Structural Dynamics, 1995, Vol. 24, No. 2, pp. 221-232, https://doi.org/10.1002/eqe.4290240207
- Tena-Colunga, A. and D. P. Abrams , "Seismic behavior of structures with flexible diaphragms", ASCE Journal of Structural Engineering, 1996 Vol. 122, No. 4, pp. 439-445. https://doi.org/10.1061/(ASCE)0733-9445(1996)122:4(439)
- Uva G., Porco F., Fiore A., Ruggieri S., Effects in conventional nonlinear static analysis: evaluation of control node position. Structures, Volume 13, February 2018, Pages 178-192. https://doi.org/10.1016/j.istruc.2017.12.006

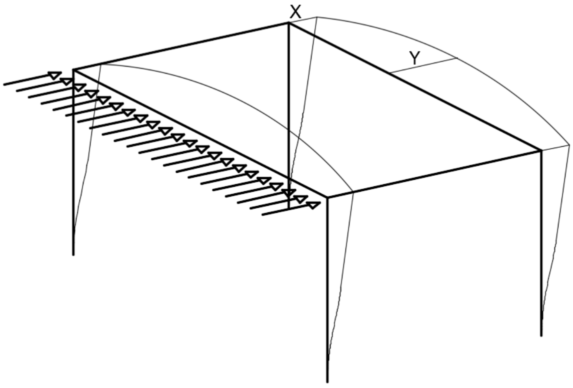


Fig. 1 – Deformed shape of structure example, under horizontal actions

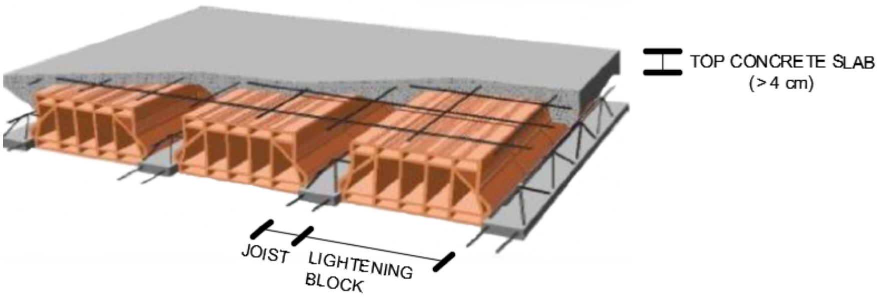


Fig. 2 – Example of typical ribbed slab

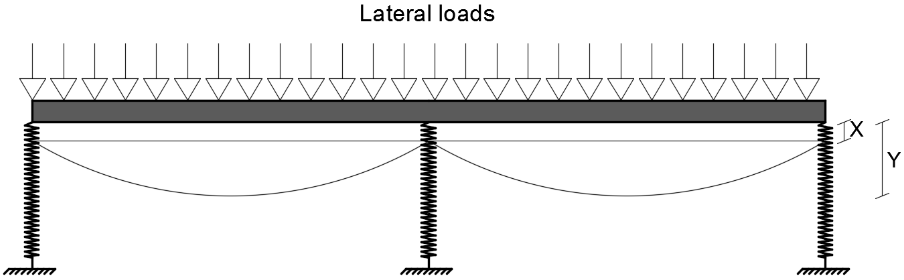


Fig.3 – Beam model

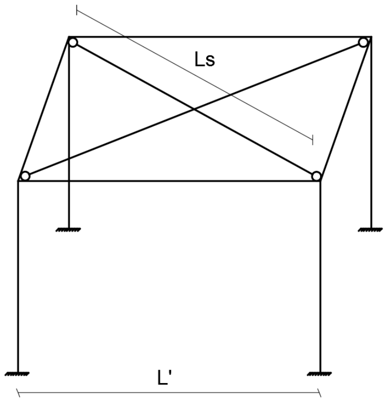


Fig.4 – Strut model

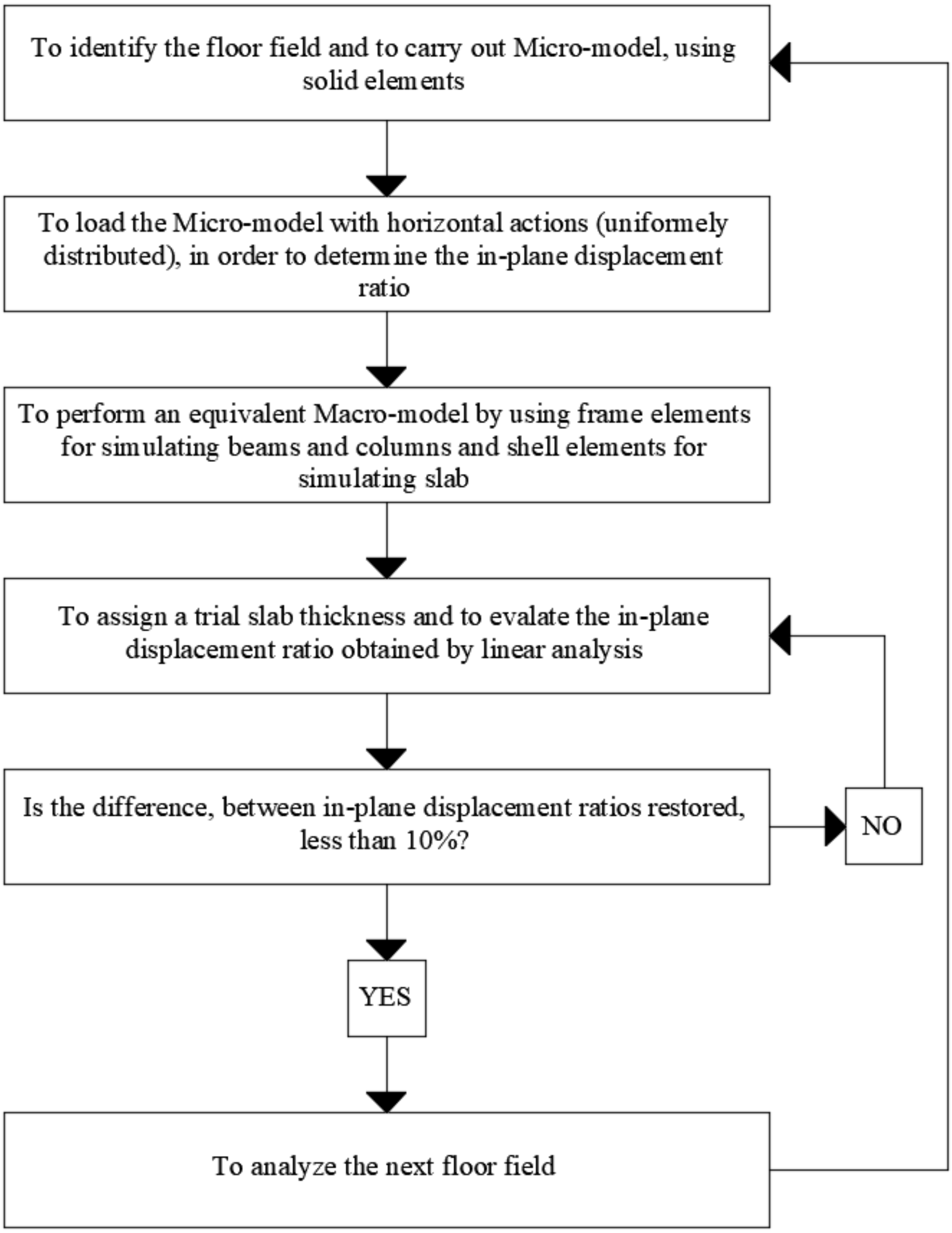


Fig 5 – Summary of new procedure proposed

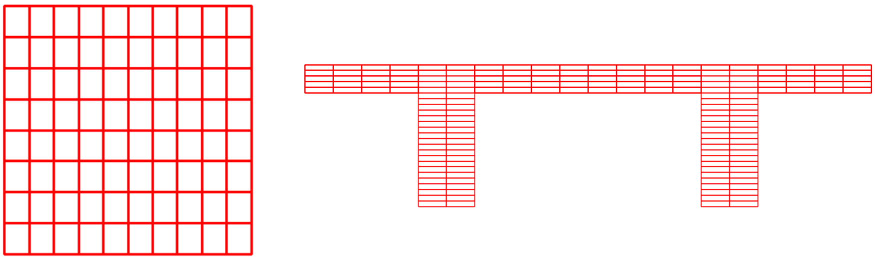


Fig 6 – Reference 3D solid model (1 mt x 1 mt), with top concrete slab of 5 cm

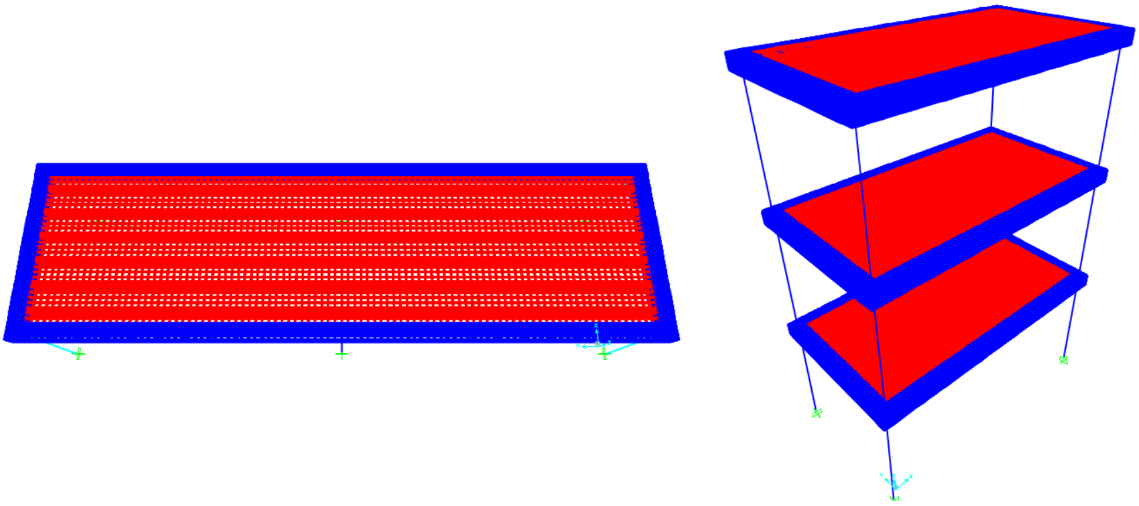


Fig 7 – Micro-models with parameters variation

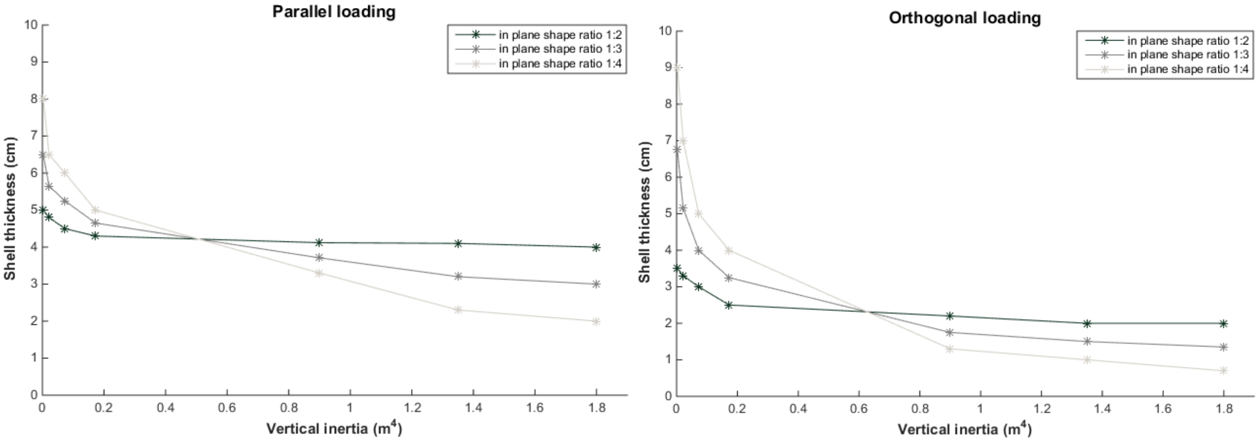


Fig. 8 – Graphs defined through preliminary analysis, to determine equivalent shell thickness (fixed top concrete slab produce equal to 4 cm; loading orthogonal and parallel)

Fig.9 – Orthophoto of case study

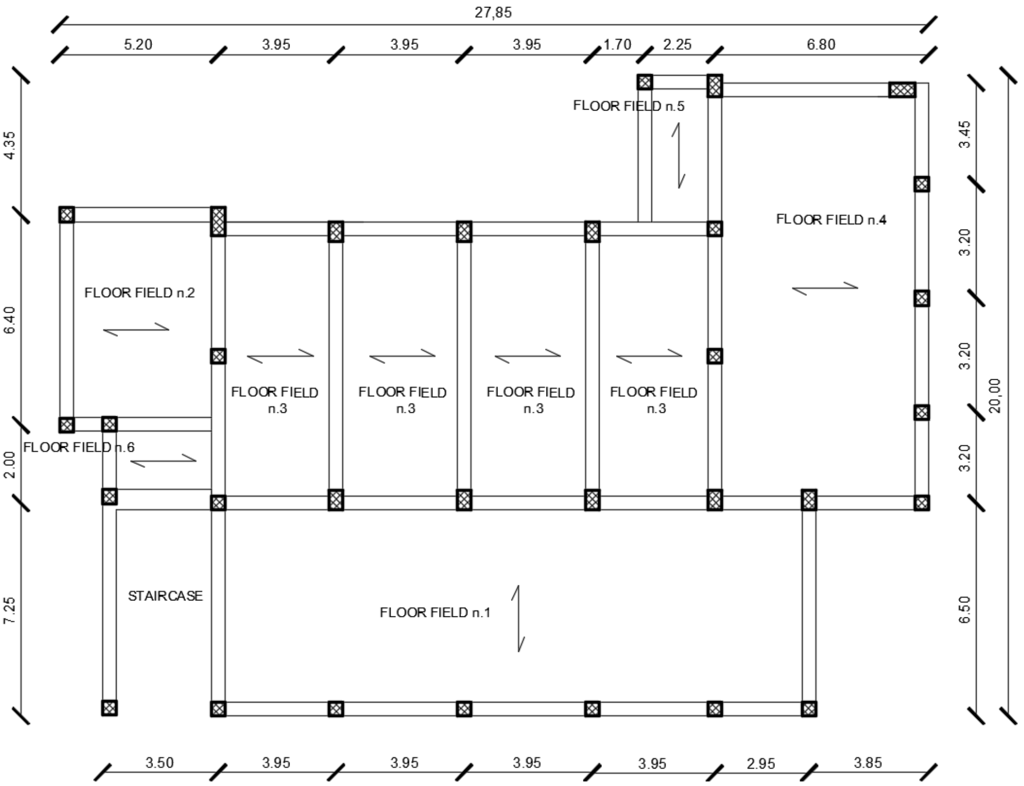


Fig. 10 – Typical floor configuration with indication of each floor field

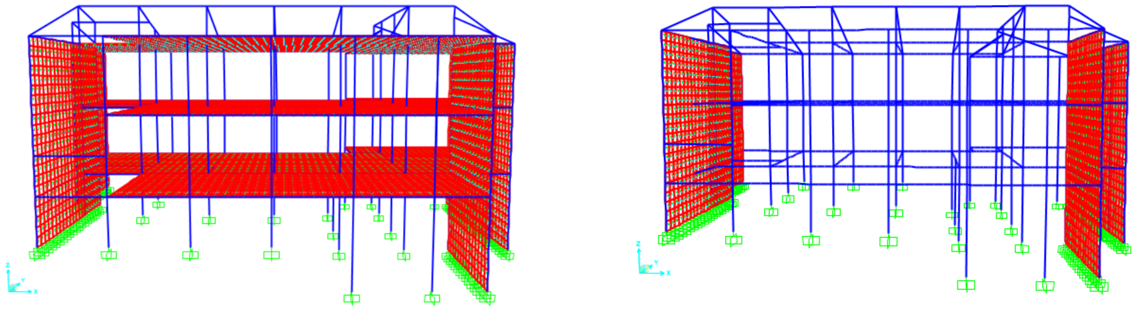


Fig. 11 – Models with RC walls

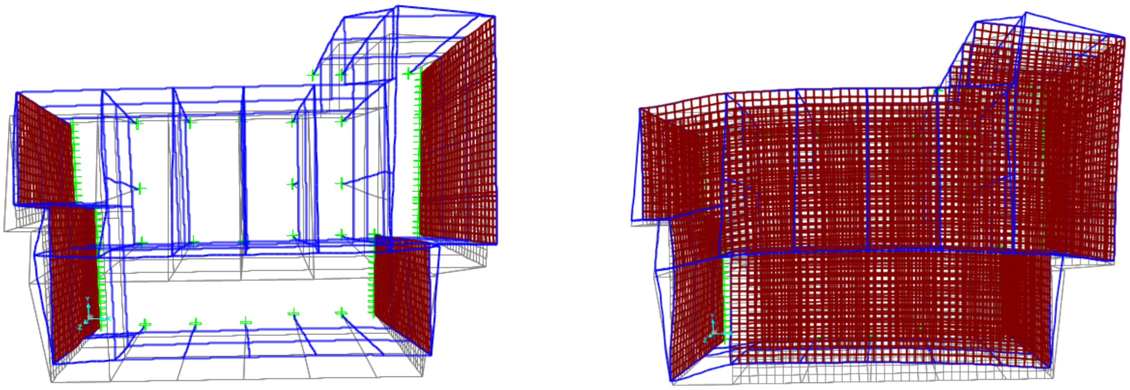


Fig. 12 – Comparison of in-plane deformed shape between models, with RC walls, with rigid floor assumption and not

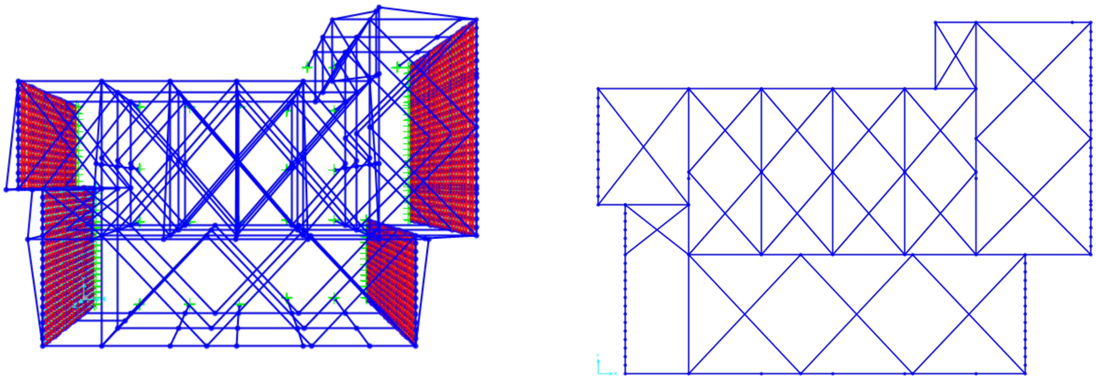


Fig. 13 – Strut model on case study

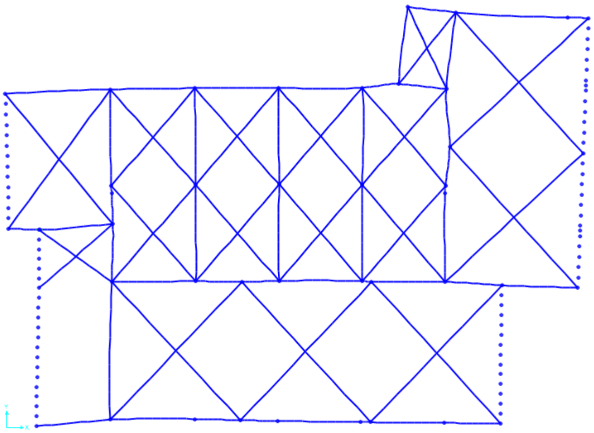


Fig. 14 – In-plane deformed shape of strut model

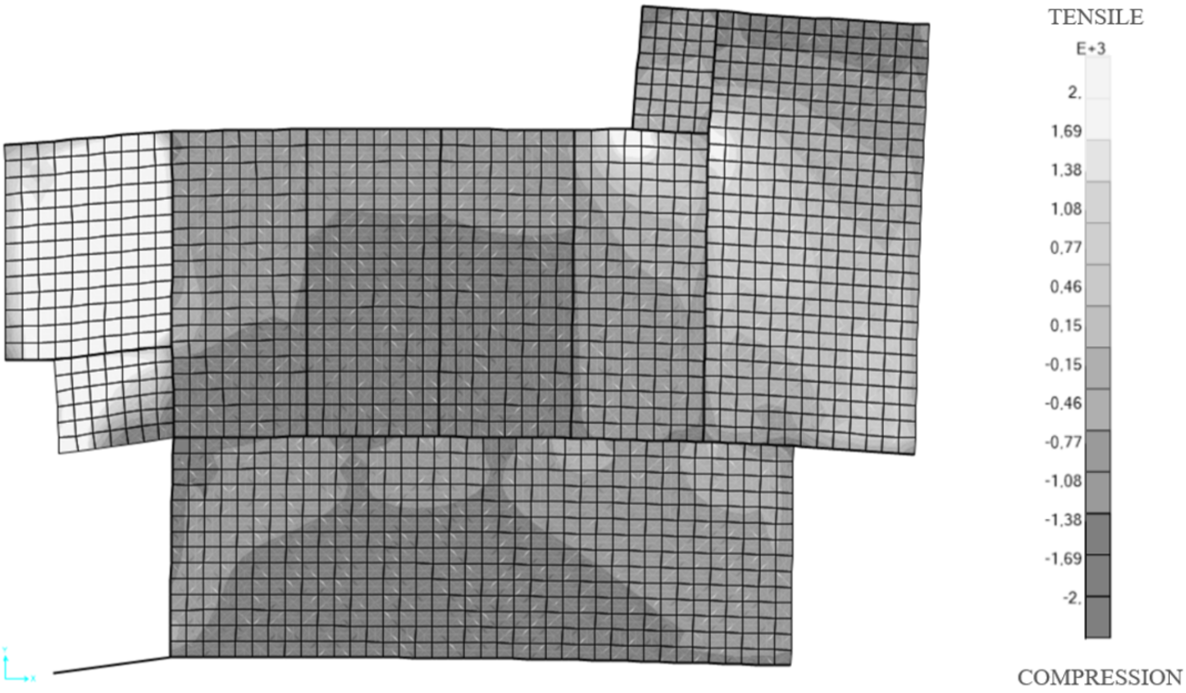


Fig. 15 – In-plane stresses state of existing building analyzed

Vertical element	Parallel direction (cm)	Orthogonal direction (cm)
Columns	30	30
	40	30
	50	30
	60	30
	90	30
	120	30
Walls	length of bay	20
	length of bay	30
	length of bay	40

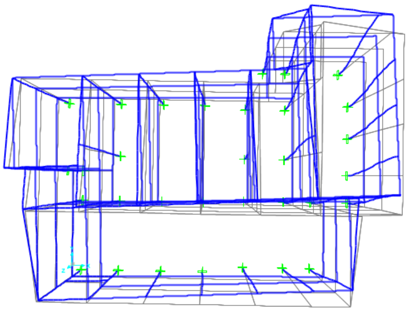
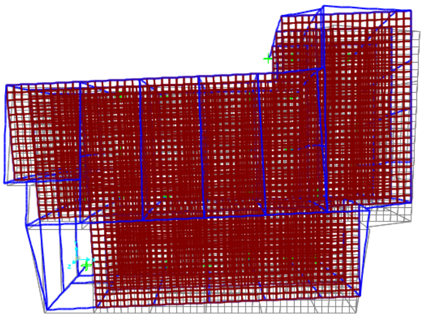
Tab. 1 – Variation of vertical elements dimensions

Level	Elements	B (mm)	H (mm)	Materials	Loads
Ground floor	*Columns*	*500*	*500*	f'_{cm}: 9,3 daN/m^2 f'_{ym}: 43 daN/m^2	$G_1 = 350$ daN/m^2 $G_2 = 250$ daN/m^2 $Q = 300$ daN/m^2
		400	*400*		
		400	500		
		400	*600*		
	Beams	*400*	*600*		
		400	*500*		
		500	*400*		
First floor	*Columns*	*400*	*400*	f'_{cm}: 9,3 daN/m^2 f'_{ym}: 43 daN/m^2	$G_1 = 350$ daN/m^2 $G_2 = 250$ daN/m^2 $Q = 300$ daN/m^2
		400	*500*		
		500	*500*		
	Beams	*400*	*400*		
		400	*500*		
		400	*600*		
		400	*800*		
Second floor	*Columns*	*400*	*400*	f'_{cm}: 9,3 daN/m^2 f'_{ym}: 43 daN/m^2	$G_1 = 300$ daN/m^2 $G_2 = 200$ daN/m^2 $Q = 50$ daN/m^2 $Q_s = 80$ daN/m^2
		400	*500*		
		500	*500*		
	Beams	*400*	*800*		
		400	*500*		

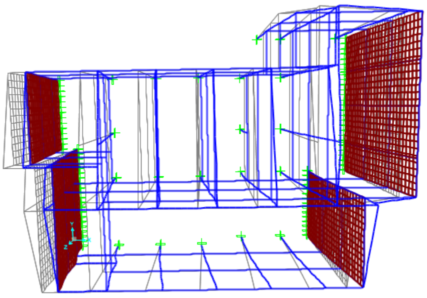
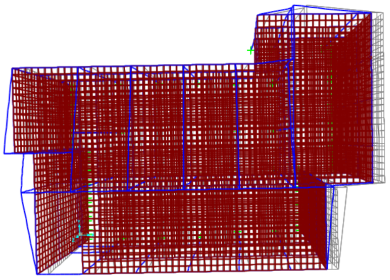
Tab.2 - Dimensions of the structural elements, design loads and mechanical parameters of materials

Floor field	In-plane shape ratio	Thicknesses (cm)	Elastic parameters (MPa)
1	1:3	Ortho = 4,3 Parallel = 5,4	$E_p = 26967{,}6$ $G_p = 13219{,}4$
2	1:2	Ortho = 3,9 Parallel = 5,0	$E_p = 27531{,}0$ $G_p = 13495{,}6$
3	1:2	Ortho = 4,2 Parallel = 5,3	$E_p = 27098{,}4$ $G_p = 13283{,}5$
4	1:2	Ortho = 3,0 Parallel = 4,5	$E_p = 32211{,}3$ $G_p = 15789{,}9$
5	1:2	Ortho = 3,2 Parallel = 4,6	$E_p = 30869{,}2$ $G_p = 15131{,}9$
6	1:2	Ortho = 3,2 Parallel = 4,6	$E_p = 30869{,}2$ $G_p = 15131{,}9$

Tab.3 – Value of thicknesses of floor fields and modified elastic parameters

1st mode - T = 0.6754 $M^*_x = 9.33\%$ $M^*_y = 52.12\%$ $M_\theta = 24.05\%$	1st mode - T = 0.6951 $M^*_x = 3.03\ \%$ $M^*_y = 62.39\%$ $M_\theta = 20.64\%$
	

Tab.4 – Comparison between models with rigid floor assumption and not

1st mode – T = 0.4565 $M^*_x = 76.22\ \%$ $M^*_y = 0\%$ $M_\theta = 0\%$	1st mode – T = 0.5467 $M^*_x = 75.67\ \%$ $M^*_y = 0\%$ $M_\theta = 0\%$
	

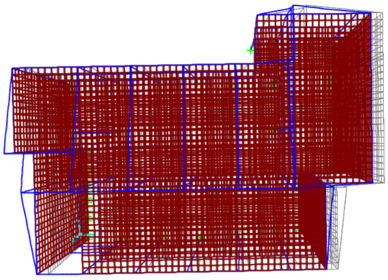
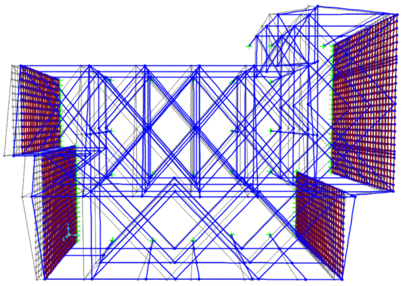
Tab.5 – Comparison between models, with RC walls, with rigid floor assumption and not

Model with rigid floor		Model with flexible floor	
$V_{b,walls}$	$V_{b,frame}$	$V_{b,walls}$	$V_{b,frame}$
98%	2%	89%	11%

Tab.6 – Differences stresses states between models, expressed in terms of total base shear percentage.

Floor field	Dimension of struts (cm)
1	35,34
2	37,54
3	45,23
4	55,85
5	35,62
6	10,76

Tab.7 – Dimension of struts

1st mode – T = 0.5467 $M^*_x = 75.67\ \%$ $M^*_y = 0\%$ $M_\theta = 0\%$	1st mode – T = 0.5625 $M^*_x = 76.18\ \%$ $M^*_y = 0\%$ $M_\theta = 0\%$
	

Tab.8 – Comparison between models, with RC walls and slab modeled using both shell and struts

	Model with equivalent shell		Model with struts	
V_b	RC walls	RC frame	RC walls	RC frame
	89%	11%	88%	12%
Modal parameters	T (s)	M*	T (s)	M*
	0.5467	75.67%	0.5626	76.19%

Tab.9 – Comparison between strut model and equivalent shell model, in terms of modal parameters and base shear