OVIDIUS UNIVERSITY

PhD. SCHOOL OF APPLIED SCIENCES

CIVIL ENGINEERING DEPARTMENT

BEHAVIOUR OF PRESTRESSED SLAB FLOORS FOR STRUCTURES LOCATED IN SEISMIC AREAS

PhD. THESIS

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1. INTRODUCTION

1.1. General introduction to the flat slab

The scope of the thesis is that of analysing the behaviour of the flat slab structures located in seismic areas, whether the slab is prestressed or not. Structures located in high seismic areas demand a specific configuration and computation methods.

One of the main principles in design of these structures is to obtain plastic hinges, hinges that are capable to dissipate energy.

In the case of traditional structures made up of columns, beams and walls the energy is dissipated by plastic hinges. The location of these hinges is well defined and known. In the case of flat slab structures in the absence of the beams this plastic hinges can appear in the slab-column connection.

Punching is another phenomenon specific for the flat slabs. The punching strength of the slabs can be improved by presstressing the concrete slab. Prestressing has many advantages also in the case of loads coming from the vertical seismic component. This is not to be neglected in the case of flat slabs that are very sensitive in the case of concentrated loads.

The paper will analyse the computation and design concepts to the flat slab structures located in seismic areas, as well as the effect of the presstressing.

Compared with other structural elements that can be made of different materials two way slabs can be made of reinforced concrete alone. In order to reduce the total height of a typical floor level different solutions have been used, such as waffle slabs, an alternative to the classic column - beam – slab system.

In 1905 eng. Claude A. P.Turner[1] was the first to use the mushroom flat slab system. He also published a blueprint according to his design (Fig. 11).

[1] Alexander Kierdorf, Early Mushroom Slab Construction in Switzerland, Russia and the U.S.A. – A Study in Parallel Technological Development

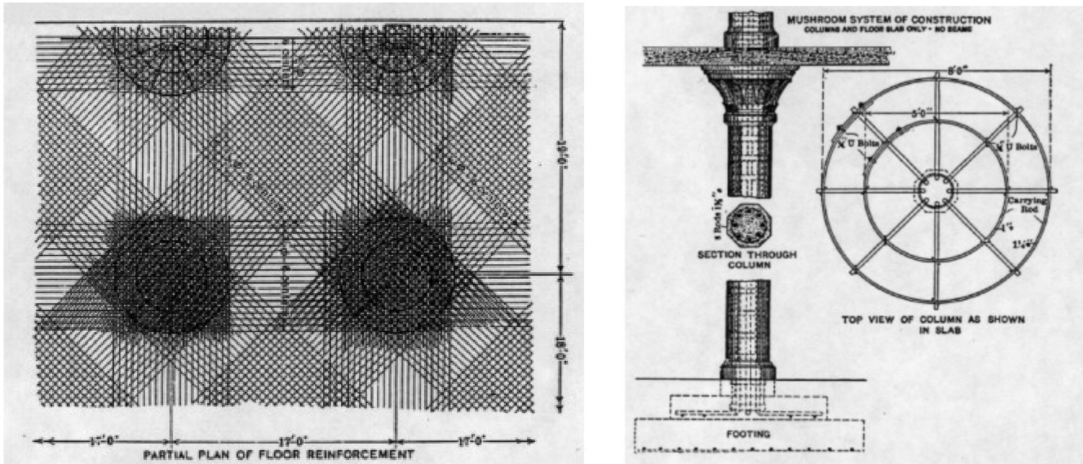


Fig. 1.1 Mushroom flat slab detail CAP Turner [1]

The first code of practice for flat slabs was published in Romania in 1952, STAS 3434 and it concerned only the gravitational design.

Depending on the support type of the column the flat slabs can be classified as:

- flat slabs without drop panel (Fig. 1.3)
- flat slabs with drop panel (Fig 1.4)
- flat slabs with mushroom drop panel (Fig 1.5)
- flat slabs with straight and mushroom drop panel (Fig. 1.6)

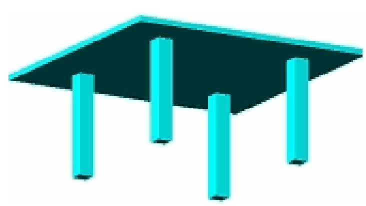


Fig. 1.3 flat slab without drop panel

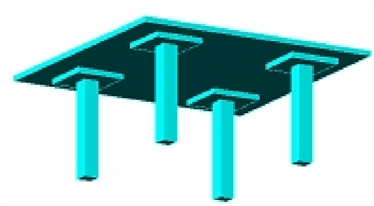


Fig. 1.4 flat slabs with drop panel

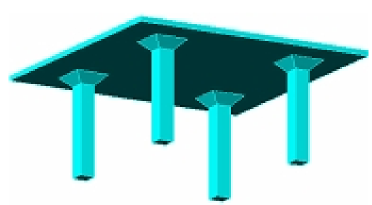


Fig. 1.5 flat slabs with mushroom drop panel

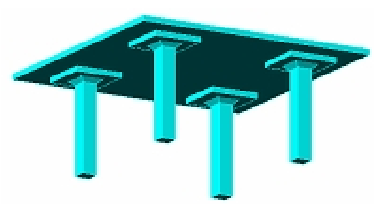


Fig. 1.6 flat slabs with straight and mushroom drop panel

1.2. Structures in seismic area. Specific typology

Reinforced concrete structures located in seismic areas, as well as the other should provide a certain set of requirements in the sense of safety, concept and economic efficiency.

According to the Romanian code P100-1/2013[2] that refers to the seismic design of the structures the following fundamental requirements are to be underlined:

- ***Life safety requirement***
- ***Reduction of the damage level***

The seismic force acting on a structure is considered to be dissipated by two energy components, elastic and a plastic one.

Generally we can speak about a few types of reinforced concrete structures such as:

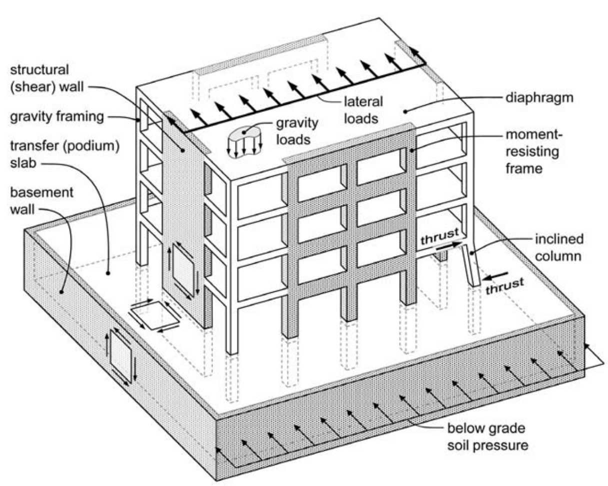
- frame were the energy is dissipated but the plastic hinges located at the columns base and at the beams ends
- structures with diaphragms were the energy is dissipated but the plastic hinges located at the walls base and at the beams ends
- dual structures having both walls and columns were the energy is dissipated by the plastic hinges located at the columns base, walls base and at the beams ends

The role of the slabs as horizontal diaphragms is to transmit the inertia loads between the vertical structural elements.

1.3 General role of the slabs in a structure. Computation of the rigid diaphragm

The slabs are surface elements that are loaded perpendicular and in their plan.

Their role is to transmit the loads to the vertical elements and horizontal elements.



[2] Cod de proiectare seismică P100 partea I - P100-1/2013 Prevederi de proiectare pentru clădiri

Fig. 1.10 The role of the diaphragms in a structure (NEHRP Seismic Design of Cast-in-Place Concrete Diaphragms, Chords, and Collectors: A Guide for Practicing Engineers)[37]

The initial approach used in the computation of the slabs was to be considered as surface elements having only normal loads that are transmitted to the beams. The horizontal component of the load was neglected initially.

For the seismic computation a very important part is consisted by the rigid diaphragm behaviour.

Generally a slab is considered to be a rigid diaphragm if the horizontal displacement of the slab is not grater then the storey relative displacement.

1.4 General flat slab structures

The flat slabs structures were used form the beginning of the concrete structures.

Some structures required this kind of solution from the very beginning of the concept. Among them are:

- liquid storage tanks
- residential and office buildings
- manufacturing shops
- parking

1.5 Flat slab structures located in seismic areas

All the structures located in seismic areas are to be designed according to the philosophy used in these specific areas.

Beside the specific requirements that were mentioned above and the ones in the SLS and ULS that are to be checked for different values of the seismic force another important problem is the one regarding the energy dissipation?

For flat slab structures the difference consists in that the plastic hinges can not be developed at the end of the beams because now most of them were assimilated by the slab. The hinges are to be directed to the bottom of the walls and of the columns.

1.6 Prestresing in concrete structures

Presstressing has been used for the concrete structures even before the Second World War. Initially the idea appeared from the need to reduce the cracks in the concrete elements.

[7]NEHRP Seismic Design of Cast-in-Place Concrete Diaphragms, Chords, and Collectors: A Guide for Practicing Engineers

A scientific approach appeared around 1928 when the French Freissynet applied for the first licence of concrete pressstresing technique.

The reduced tensile strength of the concrete is the main reason for the use of presstressing. Reinforced concrete elements are computed in cracked stage.

The use of presstressing can have many advantages such as:

- lower risk of corrosion because of the compressed concrete around the reinforcement bar
- higher strength because of the materials used
- higher fatigue strength (the concrete section is always compressed)
- formworks are no longer needed on site for the precasted elements

Presstresed concrete has also some inconveniences:

- brittle failure of the elements
- qualified personnel

Another option is the partial presstressing that has its own advantages:

- the use of the strength reserve in the concrete elements after the decompression stage
- reduced presstressing (costly operation)
- reducing the amount of the presstressing reinforcement and simplified trajectories
- reduction of concrete section because of the reduced transfer loads during presstressing, presstressing stages are eliminated
- obtaining an acceptable ductility for the bent elements (1/70÷1/80 displacement before colaps)
- a small amount of presstressing reinforcement can reduce the creep strain and combined with passive reinforcement can avoid the precamber totally

Given the above one can discuss about different stages of presstressing that are defined by the behaviour of the tensioned concrete areas or less compressed. Thus we can talk about three distinct stages:

- total presstressing when the concrete is working only in compression under the most unfavorable load combination
- limited presstressing within which the concrete can work in tension and can admit cracks of 0,1÷0,15mm under the most unfavourable load combination
- moderate prestressing is the one that can admit that the cracks under the most unfavourable load combination can be present also under normal load

conditions, but having different requirements depending of the technological requirements (reinforcement corrosion, aggressive environment, etc.)

According to CEB FIP 2010[4]Model Code [14] from the presstressing method and materials used for the tendons, steel or FRP, they can be classified as:

- internal posttenssioning pretensioned or posttensioned (adherent tendons, temporary without adherence, permanently without adherence)
- external presstressing

The components of the presstressing systems are:

- the anchorage and the coupling systems
- protection ducts
- injection materials for the protection ducts
- tensioned reinforcement

The anchorage and the coupling systems are special devices that permit the anchorage of the tensioned reinforcement in the concrete element or the continuity of the tensioned reinforcement. Function of the material used for the tendons all these elements must comply with specific requirements out of which one can mention: the capability of the tendon to reach 95% of its strength for a 2% strain in the case of steel tendons. In the case of FRP tendons the limit of 95% for the force is still valid, but a maximum value for the strain has been established.

A monostrand type T15S (Freyssinet) has the following characteristics:

Nominal diameter	mm	15,7
Area	mm^2	150
Characteristic strength f_{pk}	N/mm^2	1860
Yielding strength $f_{p0,1k}$	N/mm^2	1600
Maximum strain under maximum load ε_{uk}	%	≥ 3,5
Longitudinal sectional modulus E_p	GPa	195
Relaxation	for 1000 hours, 20°C, $0,7f_{pk}$	≤ 2,5%

Table 1.2. Characteristics of a monostrand T15S (Freyssinet)[518]

[14] FIB – Codul Model Ceb FIP 2010

The difference between the pressterssing reinforcement and the passive one is that for the first one we don't have a yielding line very well defined. The yielding point is defined as the point on the curve to which it corresponds a remanent strain of 0.1%.

The diagrams below show the stress-strain curves of the steel (warm and cold rolled steel) according to [15]:

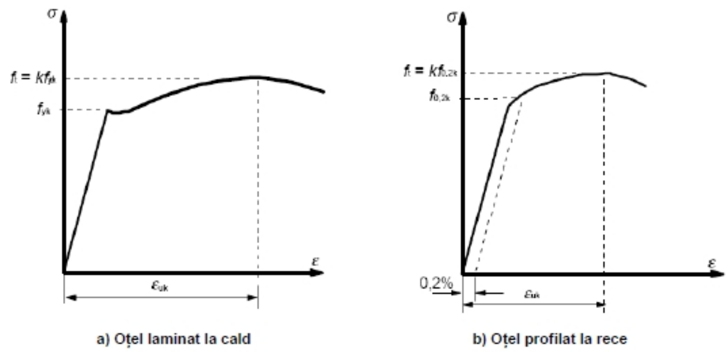


Fig. 1.23 Stress-strain curves for reinforcing steel [15]

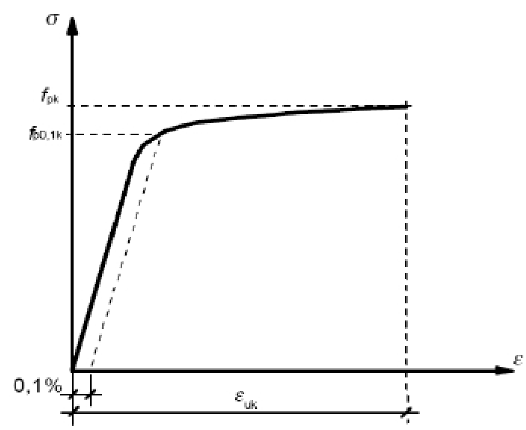


Fig. 1.24 Stress-strain curve for typical presstressing reinforcement [15]

An important use for the presstressing concrete is that for flat slabs or mat foundations. This technique can increase the punching strength and limit the cracks (very important for buildings that have parking areas inside the basements). In the case of the flat slabs (non adherent post tensioned reinforcement) there are some advantages such as bigger spans and the fact that there are no visible cracks for the permanent load combination.

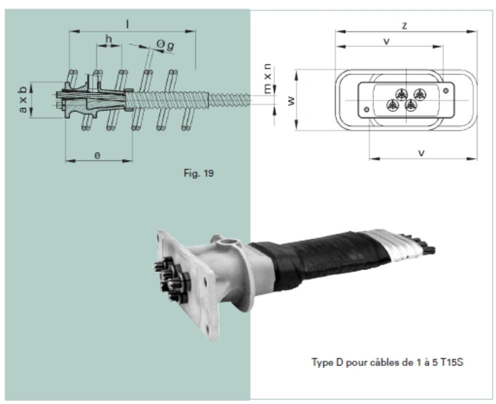
[15] SR EN 1992 – 1:2004 – Desing of reinforced concrete structures. General rulles for buildings
[18] www.freyssinet.com

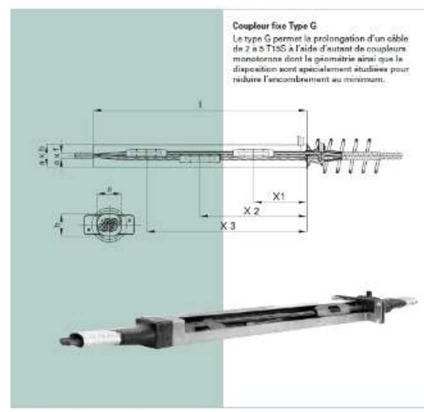
1.7 Flat slabs with post-tensioned reinforcement. General data

Since in the case of precasted elements both presstressing methods (pretensioning and posttensioning) can be applied, for the slabs, but the use of pretensioned reinforcement is applied to units only, is not a good solution because it would require costly special devices for the reinforcement anchorage.

The execution of a presstressed flat is quite similar to an ordinary reinforcement one, after the erection of the formwork the passive reinforcement is placed together with the ducts and the anchorage devices. The anchorage devices can be divided in three categories:

- active devices that allow the tensioning and the anchorage of the reinforcement
- passive devices that allow only they anchorage
- coupling devices that allow the continuity of the presstressing reinforcement





a) b)

Fig. 1.29 a) Active device Freyssinet (www.freyssinet.com) [18]
b) Cable couple

A presstressed concrete flat slab weights less than one with ordinary reinforcement. Most of the efforts induced by the permanent loads are balanced by the effect of the presstressing, another advantage of the presstressing is the reduction of the vertical deflection of the slab.

2. PRESENT STAGE IN THE FIELD OF STUDY

2.1 Computation of reinforced concrete slabs within the elastic domain

The theory of elasticity considers that the reinforced concrete slab consists of a homogenous and isotropic material. The assumption is valid during the service stage of the slab, because in the collapse stage and before it important redistributions of the bending moment appear[23].

The following hypotheses are valid for the elastic computation of the slabs:

- the median axes remains undeformed within its plan;
- a plane section normal to the axes will be plane and normal to the axes after deformation (Bernoulli hypothesis);
- the normal strains on the median axes can be neglected, $\sigma_z=0$.

2.3 Computation of concentrate loaded slabs within the elastic domain

A practical method was published by Prof. Pucher from the Polytechnic School of Wien in 1951 based on the influence surfaces (the equivalent of the influence lines) and the displacement theory of Maxwell [23].

In the case of the slabs the equation is: $\boldsymbol{w_{12}} = \boldsymbol{w_{21}}$, that means that the displacement $\boldsymbol{w_{12}}$ in point 1 due to a load applied in point 2 is equal to the displacement $\boldsymbol{w_{21}}$ in point 2 due to a concentrated load applied in point 1 (Fig. 2.4)

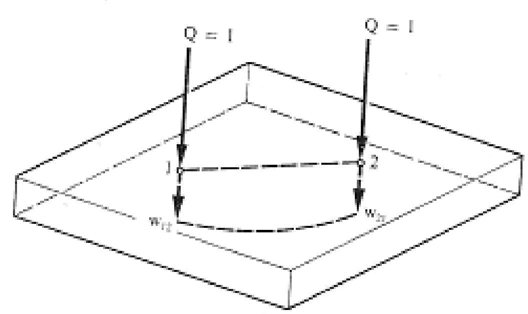


Fig. 2.4 Maxwell theory [23]

Due to the superposition theory we can say that the displacement of a slab under a concentrated is the same with the influence surface in the point where the force is applied.

2.4 Computation flat and mushroom slabs within the elastic domain

In the computation of the flat slabs and of the slabs with drop panel one will use the equilibrium principle.

An interior panel of a flat slab that is assumed to be infinite that is loaded with a uniformly distributed load is assimilated with fixed beams of length ***l*** on both directions *x* and *y*.

There are three different ways of introducing the reactions ***R*** in the slabs supports (Fig. 2.6) [23]:

- punctual support;
- support having the dimensions $d \times d = 0.1 \times l \times 0.1 \times l$ and a reaction $R = q \times l^2$, uniformly distributed on the support surface; the pressure on the support being $p = \dfrac{q \times l^2}{0.1 \times l \times 0.1 \times l} = 100q$
- support having the dimensions $d \times d = 0.1 \times l \times 0.1 \times l$ and a reaction $R = q \times l^2$, uniformly distributed on the support surface; the pressure on the support being $p = 50\ q$ and the rest of the reaction equally distributed on the four corners of the support $\dfrac{R}{8} = \dfrac{q \times l^2}{8}$

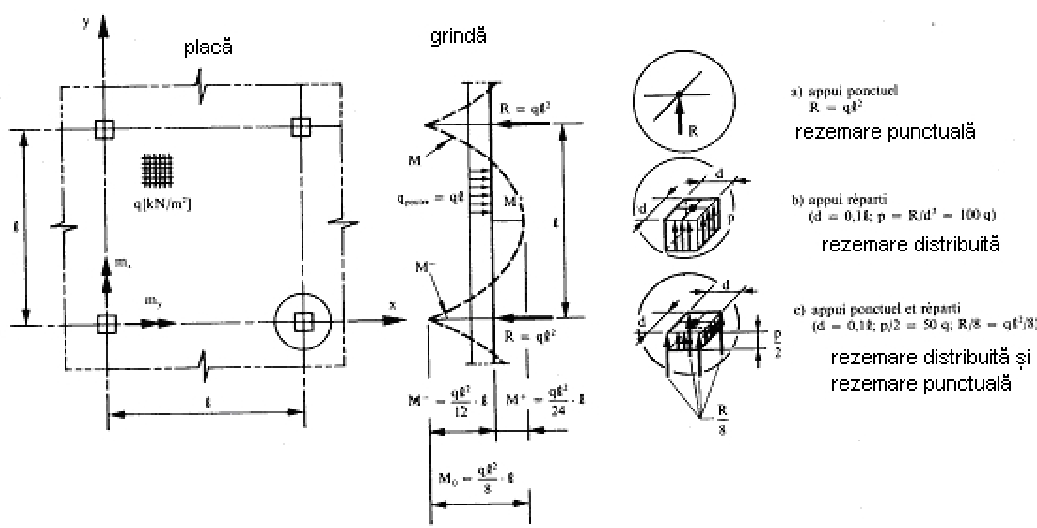


Fig. 2.6 Reactions in the slab supports [23]

The third hypothesis is the closest to the reality.

Considering the result obtained from a computer simulation for the here support types *a) concentrated support, b) distributed support, c) distributed and punctual support* for different values of Poisson coefficient ***ν***, one can conclude that it modifies the moments repartition in the support and in the field, but does not modify the global value of the moment;

at the same time the total value of the bending moment does not depend on the support type a*), b)* or *c)*.

2.5 Computation of reinforced concrete slabs within the plastic domain

The problem concern is to study the slab behaviour in the moment when the force has reached its maximum value leading to the formation of plastic hinges and subsequently to mechanism that produce the collapse of the slab if the load is increased further more.

Fig. 2.7 shows the behaviour stages of a reinforced concrete slab submitted to a progressive increasing load [23].

- *elastic behaviour stage* – (stage I).
- *cracks appear* – (stage II).
- *plastic behaviour stage*
- *collapse stage*

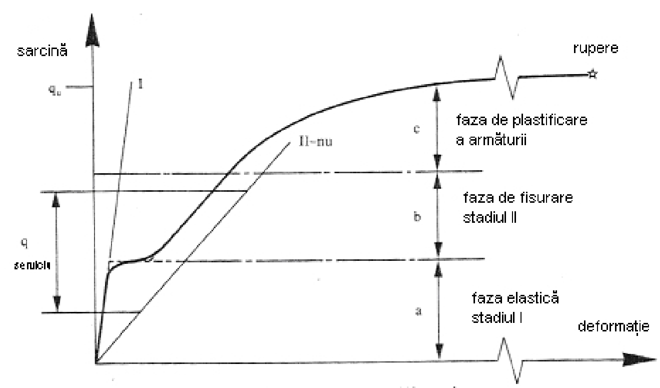


Fig. 2.7 Stress – strain deformation for a reinforced concrete slab [23]

2.8 Presstressing. Advantages

Within the chapter are developed the computation methods and their application for different structural elements as well as their behaviour under seismic actions.

As shown in Fig. 2.15 presstressed concrete elements are working in compression, the concrete is compressed or slightly tensioned without overcoming the tensile capacity of the concrete. For the case of partial presstressing the concrete is cracked during the service stage, but the opening of the cracks is very well controlled.

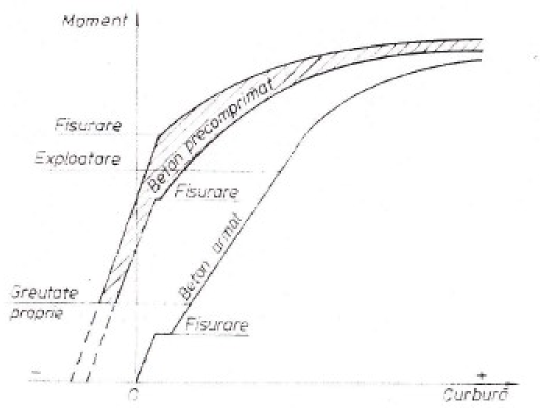


Fig. 2.15 Moment curvature digrams for presstressed concret in different prestresing stages compared to the reinforced concrete (liniary increasing loads) [12] [12]

One has to observe that presstressing has a major role in the I[st] stage and the beginning of stage II, because after the formation of the cracks it behaves as a reinforced concrete element. This can be explained by the fact that presstressing is not an external force, but an imposed deformation of the concrete element.

The use of the presstressed elements in the seismic areas is possible as long as the designer keeps in mind that it behaves different under cyclic alternant loads. The basic principles for the ductility of the reinforced concrete elements are the same for both types of elements, being

- the increase of the relative concrete compressed area within the ultimate limit stage
- reinforcement plastic deformation
- reinforcement proper anchorage
- transversal reinforcement of the section

The use of ribbed passive reinforcement in the high effort area can improve the post elastic behaviour. The same result can be obtained using partially presstressed reinforcement, but it requires more ordinary reinforcement than a fully presstressed element.

The presstresing force can improve the behaviour of a flat slab under loads perpendicular on its plan. Another aspect is the increased punching capacity. The normal effort σ that is developed in the concrete element can be assimilated to a tangential effort τ due to the principle of superposition.

12Prestressed concrete – Dan Dumitrescu, Augustin Popăescu

3. THEORETICAL AND EXPERIMENTAL RESEARCH

3.1 Theoretical research regarding the flat slabs

The previous chapter 2.5 analysed the behaviour of the reinforced concrete elements within the plastic domain. For the computation of the slabs different static or kinematics methods have been suggested.

In the following pages the methods used will be explained in detail, mainly the strip method and the collapse lines method.

The method of the collapse lines was developed by Johanssen and permits the computation of the flexural strength of a slab even for complicated geometric shapes of slabs [23].

Stair shape plastification effect of Johanses

The previous assumptions presumed that the reinforcement bars are perpendicular to the collapse lines, fact that is not true because the intersection angle has arbitrary values.

Johansen criteria is based on the assumption that after the moment when collapse lines appear each reinforcement bar plastifies on the right side of the line keeping its orientation, although the two section rotate one to the other; this is only a convention because the bars are changing their position in fact.

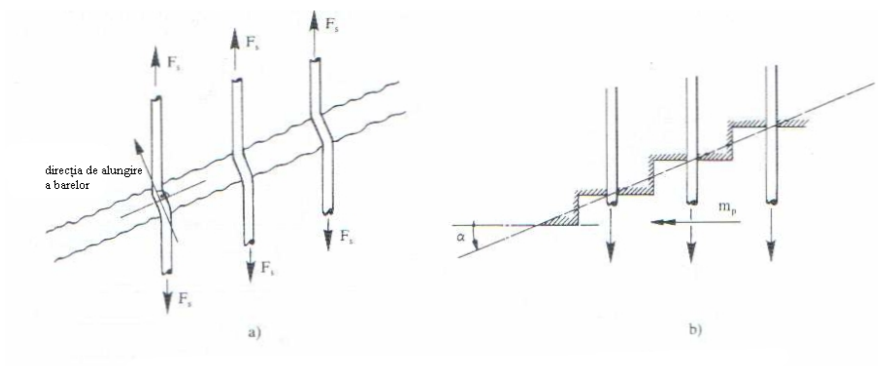


Fig. 3.1 a) Deformation of the reinforcement bars
b) Stair shape disposition of the collapse lines [23]

Kinking effect – Wood criteria

As shown above Johansen theory is based on the assumption that the reinforcement bars plastifie along their initial direction. Wood suggests other criteria that suggest the fact that the bars plastify perpendicular to collapse lines (Fig. 3.4).

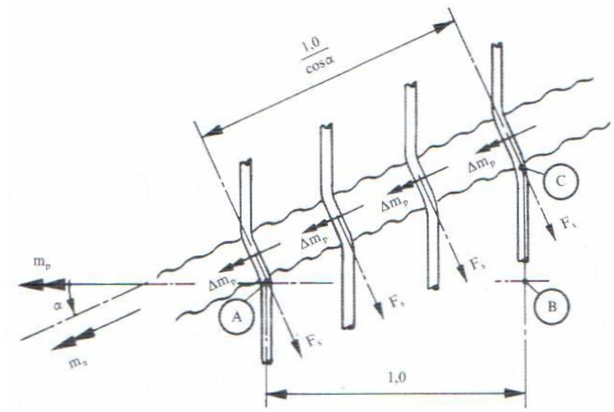


Fig 3.4 Wood Kinking effect [23]

Johansen theory was contested by the scientific community; the experiments confirmed a certain deviation of the bars along the collapse line, while Wood suggests that the bars are perfectly fixed in the concrete element [23].

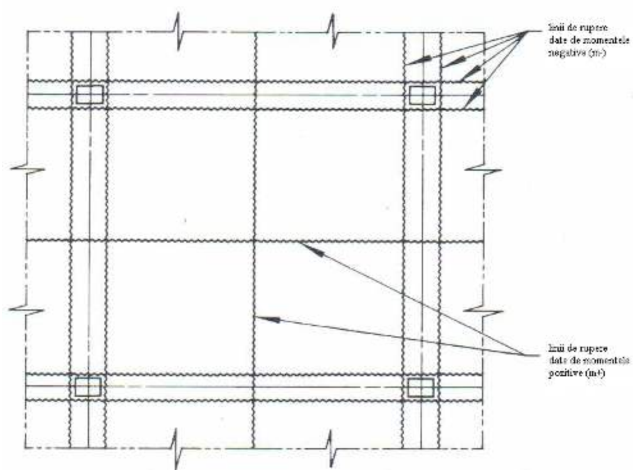


Fig. 3.7 The collapse lines of an interior flat slab panel [23]

Strip method is considered to be a relatively simple application of the static method, given the second complexity and of the fact that it provides values close to the lower bound of the safety. Even though using the strip method one obtains the maximum values of the efforts it is used because it can be easily applied.

3.2 Computation of flat slabs

Flat slabs can be computed using the above methods if the columns have a regular disposition. That means that the following conditions are to be satisfied [23]:

$$0.67 \leq \frac{l_y}{l_x} \leq 1.5$$
$$0.75 \leq \frac{l_{x1}}{l_{x2}} \leq 1.33$$

, where l_x, l_y, are the spans between the columns, respectively the distance between the axes l_{x1}, l_{x2}.

For this kind of slab we have two mechanisms:

I

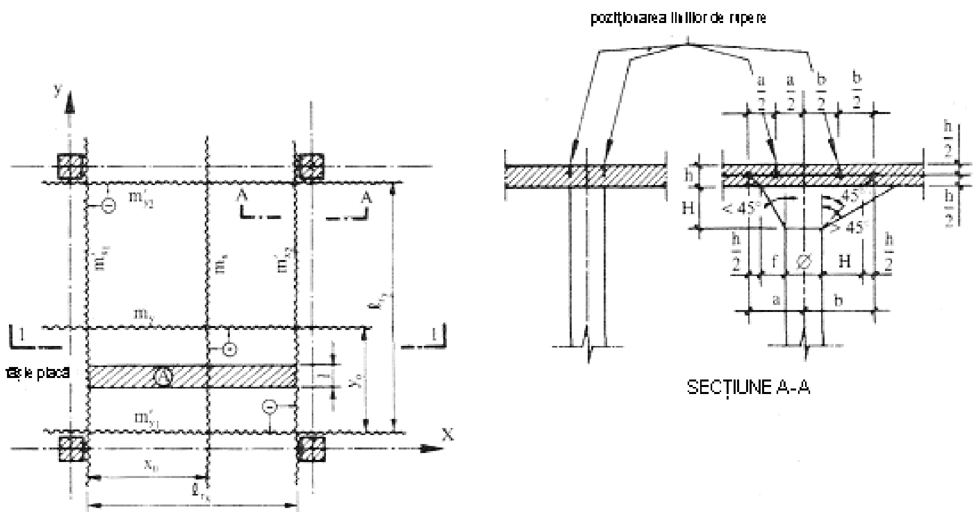


Fig. 3.10 Collapse lines disposition in a global mechanism (I^{st} type mechanism) for an interior span [23]

The local mechanism deals with the effects of a concentrated force on a slab span [23]. In the case of an isotropic slab the solution obtained can be an exact one.

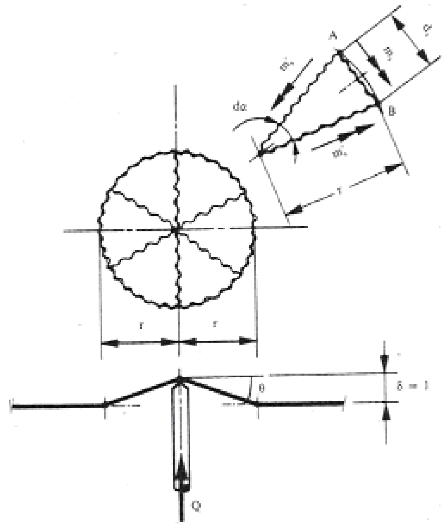


Fig. 3.12 Local mechanism [23]

In general for a slab having a constant depth supported by a column the collapse line has the shape on ellipse (Fig. 3.12).

Slabs collapse by punching is a phenomenon specific to the flat slabs and mat foundations. It appears due to a high value force applied on a small area. The computation methods are quite similar for all the existing codes, the differences consists in the formulas and the safety coefficients, the general design philosophy being the same.

The European standard Eurocode 2 defines the punching perimeter, u_1 according to (Fig. 3.14).

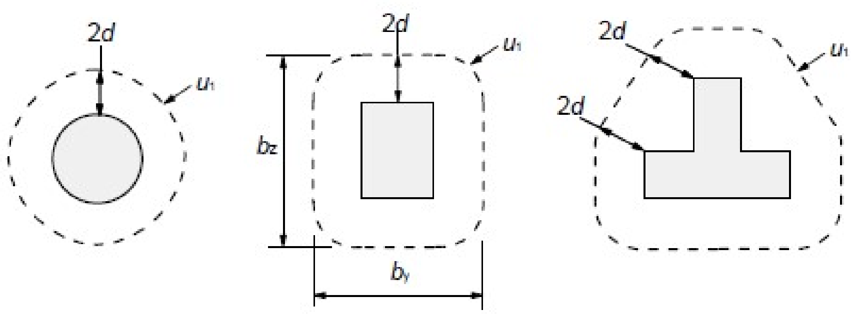


Fig. 3.14 Punching perimeter for columns of different shape [15]

The shape of the column is an important factor. It was shown that the square shape columns have a punching capacity 15% smaller than the circular ones. The punching capacity continues to decrease as the ratio between the sides of the column increases.

(Fig.32) illustrates the punching collapse of a slab supported by a circular column. The radial cracks and circular crack that bounds the punching cone are visible. All the experiments and the collapse events that appeared on field showed that the punching of the slabs is a brittle phenomenon.

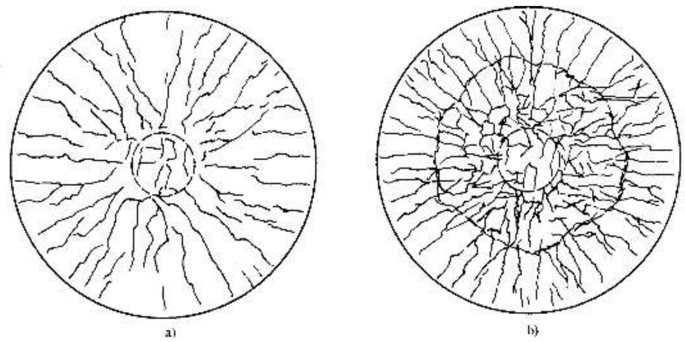


Fig. 3.22 Punching cracks around a column [23]

a) cracks formed under the service loads 680 kN

b) cracks formed under the ultimate loads 1649 kN

Given the complexity of the phenomena one must provide a flexural reinforcement and reinforcement for the punching efforts. An alternative method that can reduce the danger of punching is the use of drop panels.

Presstressing can improve the behaviour of the slabs around the columns, the deflection of the strands leads to efforts that are opposite to the punching ones (Fig. 3.25). In order to consider a reduced value for the punching force the curvature of the presstressing reinforcement should get over the column perimeter for at least the active height of the slab (d_m).

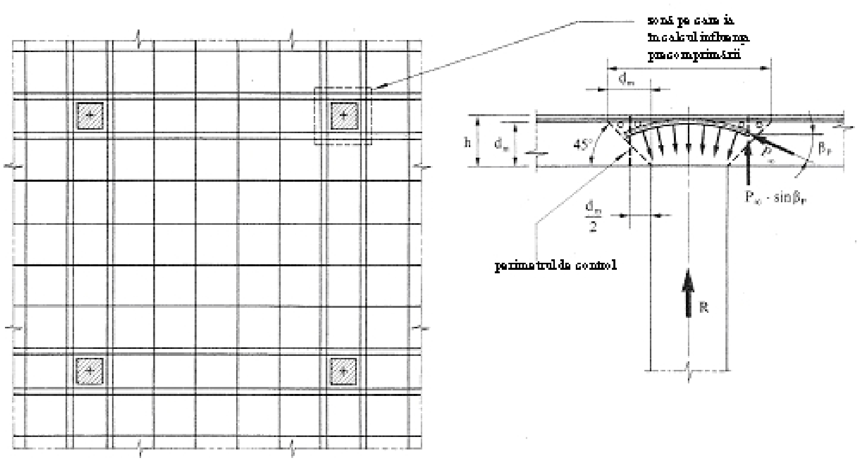


Fig. 3.25 The effect of the presstressing up on the support area [23]

Within the daily engineering computations two different methods are used [26]:

The coefficients method, know as well as the direct method uses coefficients that varies function of the support type of the slab and on the ratio between the column edges. This method is a very good one and the results obtained are very close to the reality, but it can not be applied for presstressed slabs.

The equivalent frame method, assumes that the structure is divided into equivalent continuous frames centred on the columns that extend on both sides (Fig. 3.26).

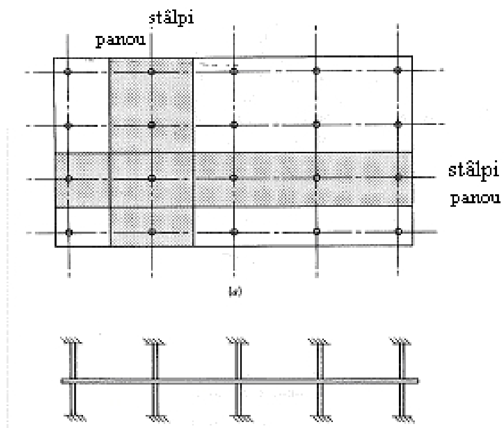


Fig. 3.26 Equivalent frames method[7]

3.3 Computation of presstresed concrete flat slabs

The use of the posttensioned reinforcement for reinforced concrete slabs has different economical and technical advantages such as:

- slender structures
- bigger spans
- smaller deflections
- reduced crack opening
- improved fatigue behaviour

Disposition of the posttensioned reinforcement

There are two different layouts for the disposition of the presstressing reinforcement (Fig. 3.28) [23]:

- distributed prestressed reinforcement
- concentrated prestressed reinforcement within the support strip

[7] GP 118-2012 – Guide for the design of flat slabs in seismic areas

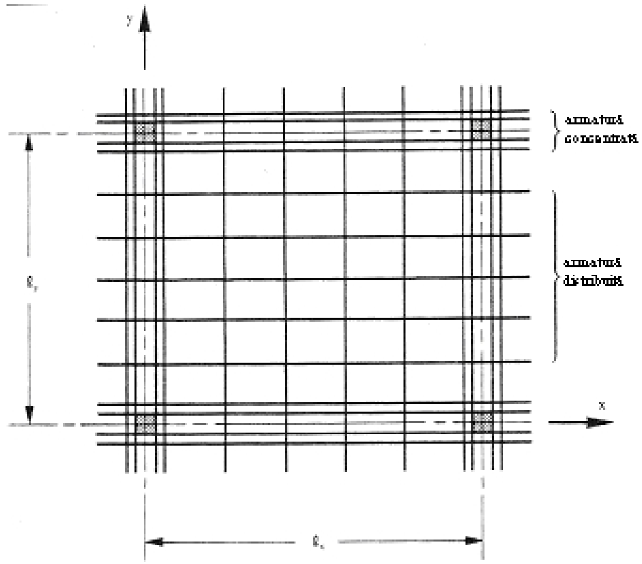


Fig. 3.28 Layout of the presstressed reinforcement in flat slab [23]

In practice it is very common to find a combination between the two methods.

Prestressing without adherence

Presstressing of flat slabs is favoured by the use of a large number of strands with a smaller diameter and bigger eccentricity (Fig. 3.30) [23].

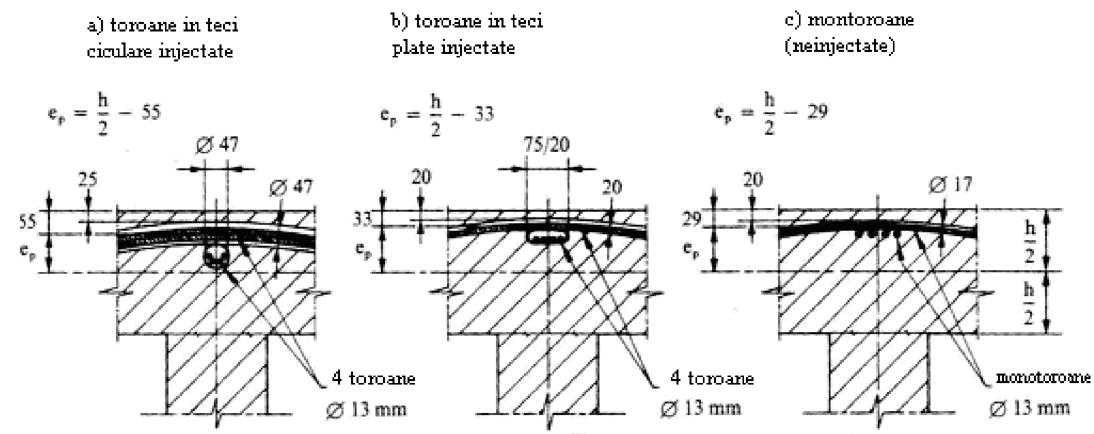


Fig. 3.30 Comparison between the eccentricities obtained with different presstressing reinforcement [23]

Because of the high costs of injection and corrosion protection monostrands are preferred. Monostrands are protected against corrosion by plastic ducts filled with grease.

Monostrands do not have adhesion to the concrete. In this case the tension efforts are transmitted from the monostrands to the concrete only by anchorages.

An efficient use of the reinforcement can be obtained by using a high concrete class and a reinforcement ratio of 0,2% – 0,3% for the tensioned reinforcement. Considering that in the case of reinforced concrete elements the reinforcement ratio is about 0.5% the use of high class concrete is justified, even if it has a higher cost. The European standard limits the compression efforts within the concrete to 0.6-0.7 of the concrete characteristic compression strength.

The minimum percentage of passive reinforcement has to computed keeping in mind that when the cracks are formed it has to yield (only in the case of small percentage of passive reinforcement). This criterion does not take into account the cracks opening.

3.4 Behaviour of flat slabs structures in seismic areas

The main requirements that are to be satisfied by the structures located in seismic areas are the rigidity, displacement, strength capacity, post-earthquake behaviour and the energy dissipation.

For a frame structure one can assume that the plastic hinges will appear at the end of the beams and at the base of the structural elements. In the case of a flat slab structure their number is educed by the lack of beams.

Present studies and codes recommend the use of perimetral beams for structures with at lest three storeys, located in area with low seismic activity, and for structures having two storeys, for high risk seismic areas [26].

Another restriction is given by the imposed small relative displacements, requirement that is important due to the second order effects that may arise during the seismic event.

For frame structures it should be analysed also the problem of short columns, that are very sensitive to shear. The slabs acting are acting as horizontal diaphragms.

For such structures the ductility that can be taken into account is quite reduced. The studies suggest the following ductility coefficients.

Table 3.3 Ductility coefficients for structures locate din seismic areas [26]:

Type of structure	Ductility class H (q)	Ductility class M (q)
Frame structures with flat slabs	3,5(α_{11}/ α_1)	2,5(α_{11}/ α_1)
Dual Structures	4,0(α_{11}/ α_1)	3,0(α_{11}/ α_1)

Punching of the slabs can generated the general collapse of the structure. In order to avoid these phenomena a supplementary reinforcement is needed. Its role is to hang the slab in the case that the punching effect took place [26].

Presstressing can improve the shear force capacity of the flat slabs. For structures located in high seismic areas the maximum drift varies form 1% for immediate occupancy and 4% for the ultimate limit state, for a frame structure [26].

During the test the presstressed slabs shown an increased capacity of plastic rotation in the column hinges from 0.02-0.03 for reinforced concrete to a value of 0.2 between the capacity and the requirements from the gravitational loads. A major increase in the performance was observed for the situation when the strands pass over the column from both directions; a value of 0.2 between requirement and capacity for a maximum drift of 5%. The drift is however restrained due to life safety requirements [29].[829]

One can say that the flat slab structures can have a satisfactory behaviour in seismic area as long as specific requirements are obeying. The main problems of this kind of structure are the punching and the fracture of the column from shear.

3.5 Computation of flat slab structures

Due to the reduced plastification capacity of the flat slabs it is necessary to provide perimetral beams between the columns. In this case it is mandatory to realize only ground floor structures in high seismic areas [26].

For multiple storey structures it is necessary to use structural walls.

Flat slab structures do not have the same capacity to dissipate energy by the horizontal elements like the frame ones. The design philosophy should consider that the plastic hinges should form at the base of the columns and of the walls.

Another phenomenon that must be considered is the reduced rotation capacity of the flat slabs that can be improved by the use of the transversal reinforcement. The moment equilibrium check should be done as well.

The reduction coefficients for the materials are different than the ones use for reinforced concrete structures.

Table 3.4 Design values of the sectional rigidity for structural elements [26]

Element type	SLS		ULS
	Non structural elements	Non structural	

[29] Pacific Earthquake Engineering Research, Slab-Column Frames, John Wallace

	are taken into account for the overall structural rigidity	elements do not interact with the structure	
Slabs (finite elements design or equivalent beams)	0.4 EcIc	0.3 EcIc	0.3 EcIc
Perimetral beams	0.6 EcIc	0.4 EcIc	0.4 EcIc
Columns	0.5EcIc	0.5 EcIc	0.5 EcIc
Structural columns	0.5 EcIc	0.5 EcIc	0.5 EcIc

Ec – Concrete sectional modulus

Ic – Moment of inertia of the gross (uncracked) section

3.6 Comments up on the research report of European Commission Joint Research Centre (E.C.J.R.C.)

Pseudo dynamic test on a flat slab reinforced concrete structure

The paper used for the analysis of reinforced concrete flat slab structures is a report provided by European Commission Joint Research Centre – Institute for the Protection and Security of the Citizen European Laboratory for Structural Assessment (ELSA) I- 21020 Ispra (VA), Italy, entitled “Pseudodynamic Earthquake Test on a Full-Scale RC Flat-Slab Building Structure”, authors: R. Zaharia, F. Taucer, A. Pinto, J. Molina, V. Vidal, E. Coelho, P. Candeias[9][30].

Experiment description

The purpose of the experiment is to determine the behaviour of the reinforced concrete flat slab structures under seismic actions.

The Portuguese code of practice [REBAP, 1983], [RSA,1983] was used in the design.

The structure has the maximum dimensions 8.50 m x 5.20 m, as shown in Fig. 3.34, and three storeys height. The vertical elements consist of two types of columns 0.30 m x 0.50 m at ground floor and first level and 0.30 m x 0.40 m at the second and at the third level.

[30] “Pseudodynamic Earthquake Test on a Full-Scale RC Flat-Slab Building Structure”, autori: R. Zaharia, F. Taucer, A. Pinto, J. Molina, V. Vidal, E. Coelho, P. Candeias.

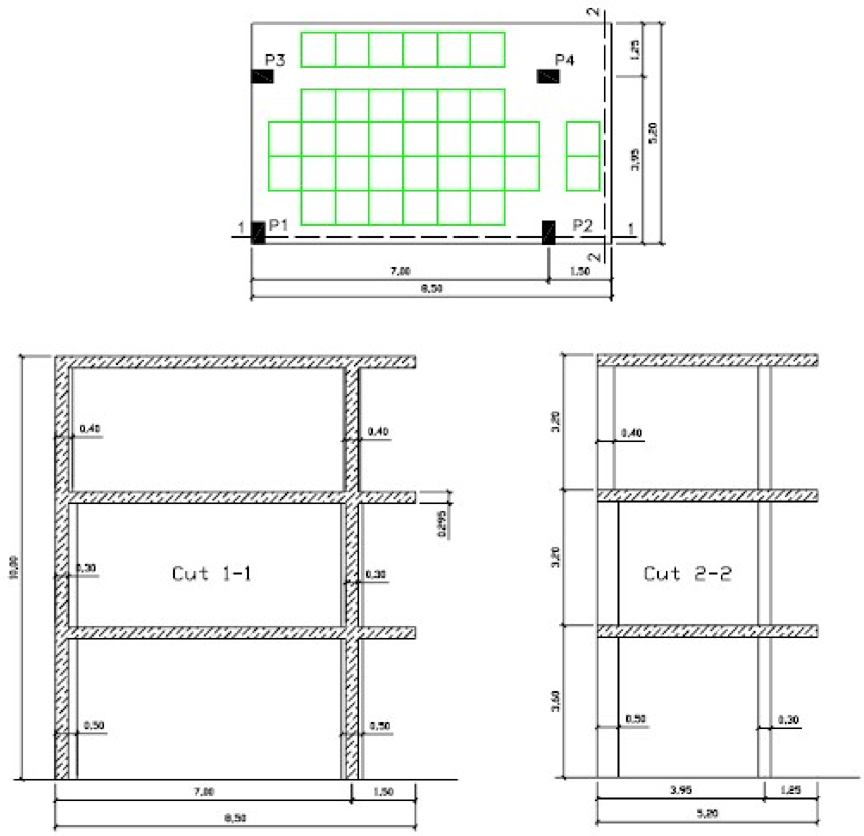


Figure 1. Plan and elevation views of the flat-slab building

Fig. 3.37 Plan and elevation view [31]

The slabs 30 cm thick were constructed as waffle slab in order to reduce the weight (Fig. 3.35), (Fig.3.36).

Materials used and their properties

The materials used are: concrete class C25/30 and reinforcement class A400 (Feb44k) having the following characteristics determined on different samples (Fig. 3.40) and (Fig. 3.41), (Fig.3.42).

Earthquake loads (accelerograms)

For the simulation of the earthquake events two pseudodynamics test were used for 20 sec. duration with a force corresponding to moderate seismic load.

The first one used an earthquake with a PGA=0.16 g and 475 years recurrence period (Fig. 10).

The second one has a PGA = 0.277 g and 2000 years return period.

To obtain the structural response to a seismic action an artificial accelerogram is considered in the computations and than the structure is pushed by hydraulic jacks until the corresponding displacement is achieved.

Numerical analysis method

In order to obtain different results for the structure there have been done different numerical simulation for seismic events with a return period of 475 years and 2000 years.

The following results have been obtained for the 475 years return period earthquake:

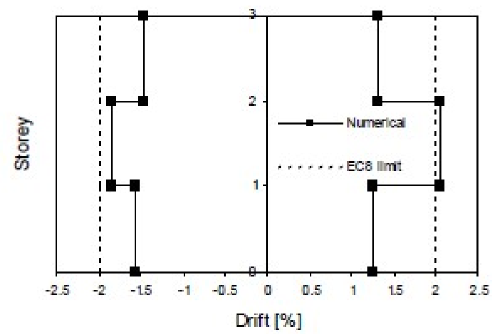


Figure 16. Maximum inter-storey drift profile

Fig. 3.5 Maximum inter-storey drift profile [31]

The following results have been obtained for the 2000 years recurrence earthquake:

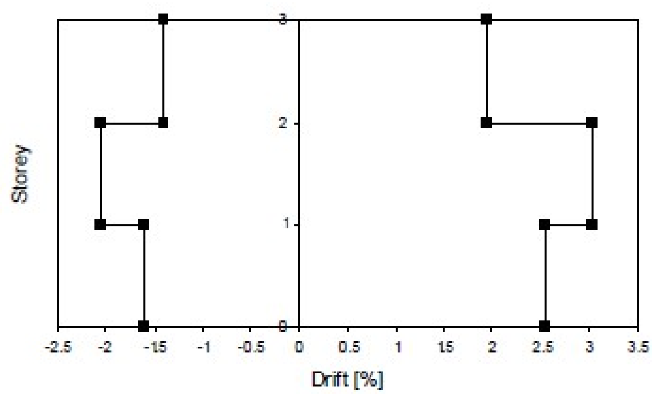


Figure 20. Maximum inter-storey drift profile

Fig. 3.51 Maximum inter-storey drift profile [31]

Experimental results

Experimental results for the earthquake having 475 years return period

After the application of the force the following structural damages have been observed:

- cracks form the bending moment in the principal beams, both transversal and longitudinal
- important cracks on the inner face of the slab over the 3rd floor
- cracks due to the bending moment in the upper part of the slabs next to the columns at level 1 and 2
- cracks at the base of the columns

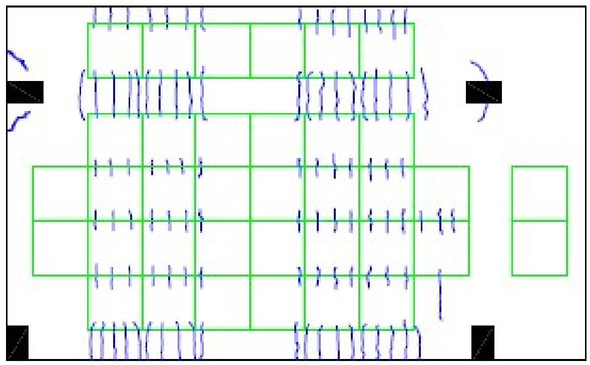


Figure 23. Floor 3 (below): cracking pattern

Figure 24. Floor 3 (below): slab crack detail around the perimeter of column P3

Fig. 3.54 Cracks on the inner face of the slab for column P3 at the 3rd level [31]

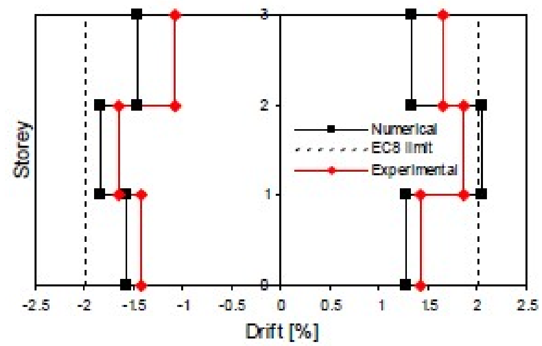


Figure 37. Maximum inter-storey drift profile (%)

Fig. 3.58 Maximum inter-storey drift profile (%) [31]

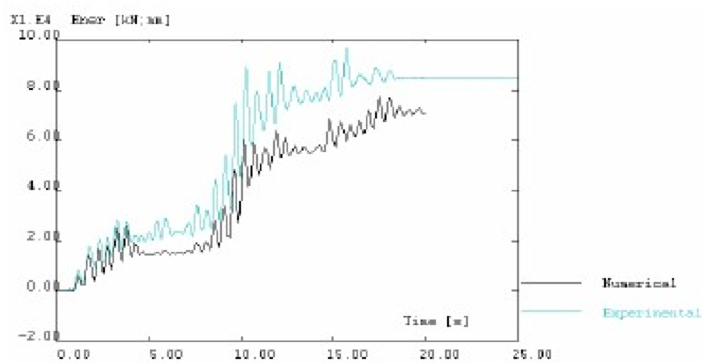


Figure 51. Total energy dissipation (experimental and numerical)

Fig. 3.59 Total energy dissipation (experimental and numerical) [31]

Experimental results for the earthquake with 2000 years return period

As mentioned before in order to obtain the effects of the seismic force a certain displacement has been imposed to the structure. For the 2000 years return period earthquake the 400 years earthquake displacement was multiplied by a factor equal to 1.73.

Because the structure was already damaged by the first experiment the damages were greater than in the first case, some of them being:

- important cracks at the outer face of the column-slab connexions
- cracks due to the torsion of the transversal beams, as a result it was the collapse of the column-slab connexion
- the cracks around column P1 and P3 opened more as a result of the positive moments

- important cracks were observed at the base of the columns
- concrete cleavage and reinforcement buckling were noticed as well

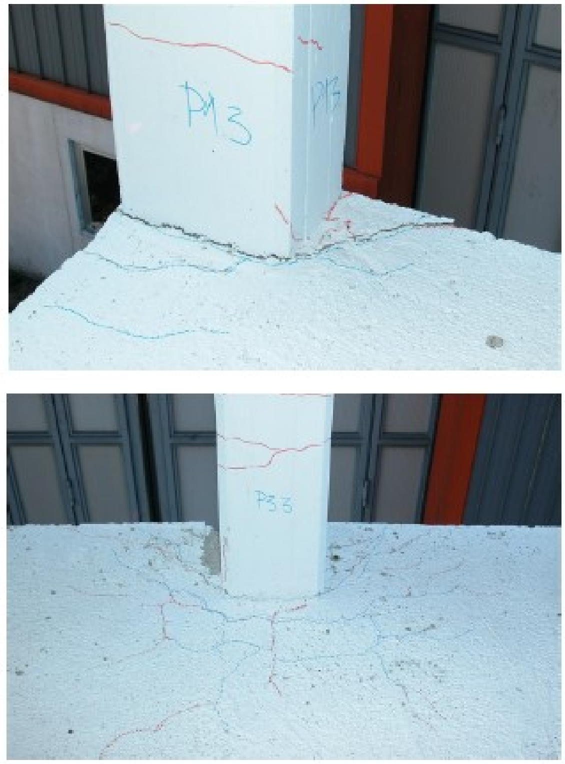


Figure 56. Floor 2 (above): details of cracking around columns P1 and P3

Fig. 3.60 Floor 2 (above): details around columns P1 and P3 [31]

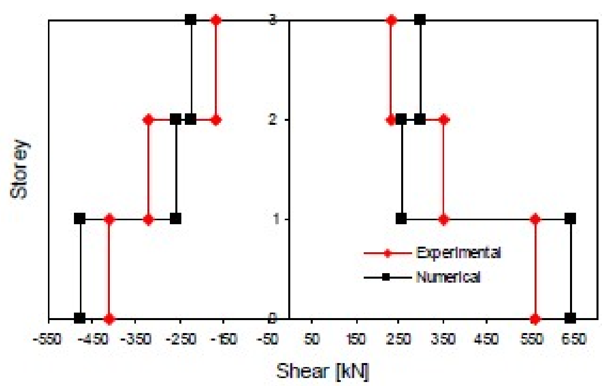


Figure 74. Maximum storey shear profile (kN) – experimental & numerical

Fig. 3.70 Maximum storey shear profile (kN) [31]

Push-over analysis

A push-over analysis was run during the experiment for two situations, when the structure was pushed to or against the wall.

The results show important differences between the first and the second order analysis. Thus one can say the first order analysis considers a greater resistance to yielding compared with the second order analysis emphasising the importance of the second order effects in the stiffness of the structure.

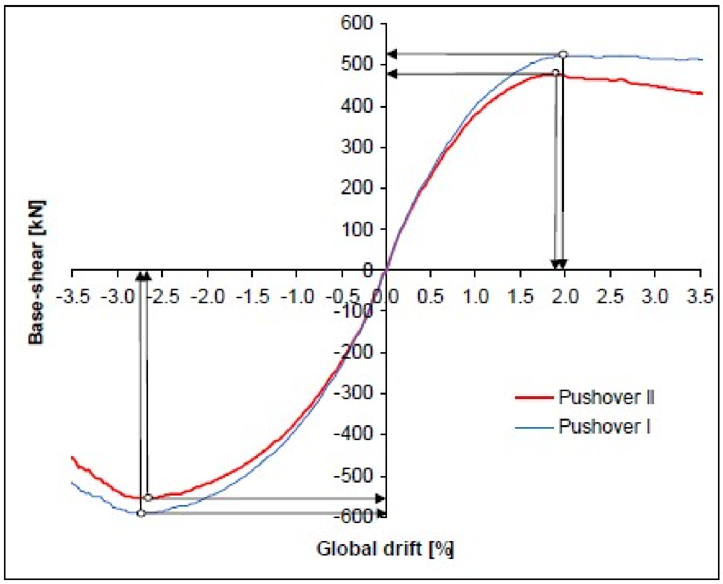


Figure 100. Base-shear versus global drift
(Pushover I: First order analysis, Pushover II: Second order analysis)

Fig. 3.72 Base-shear versus global drift [31]

Experiment conclusions

The main conclusions of the experiment are the following:

- the majority of the deformations concentrated in the area around the column slab connexion
- important cracks appeared because of torsion and bending efforts
- important dammages from torsion appeared in the transversal beams of the side columns and fewer at the inner columns
- the slab was separated from the columns (punching) due to the insufficient reinforcement

The active width of the slab is very important and must be evaluated carefully from the beginning.

The slab has a reduced role in the seismic behaviour of the structure than the one considered by Eurocode 2, thing that has been confirmed also by recent studies.

Flat slab structures are more flexible than the frame structure that is why the codes recommend the use of structural walls.

Comments upon the pseudo-dynamic test on a flat slab reinforced concrete structure

As mentioned above the flat slab structure does not have a good behaviour when subjected to lateral displacements.

During the test the structure was subjected to lateral displacements, the same as in the case of a seismic action.

The experiment emphasised more problems that can appear for such a structure.

Slab-column connexion

One the weak points for such a structure are the slab-column connexion.

The slab-column connexion can not be compared form the energy dissipation point of view with the beam-column connexion. In this case only part of the reinforcement is considered to work in bending, due to the insufficient anchorage that can allow the slab to disconnect form the column.

In the case of the cantilevers, where the reinforcement had a longer anchorage length the disconnection did not appear any more. The cantilever was able to redistribute and equilibrate the bending moment. The USA code has also a provision that recommends that the slab should extended over the connexion.

It should be noticed that the damages of the slab-column connexion did not appear due to the gravitational loads, but because of he alternate lateral displacements. Thing lead to the appearance of the negative moments and the end to the damage of the connexion. If for the classic connexion beam-column the compressed concrete area is big, as well as the reinforcement area allowing big bending moments in the case of flat slabs this is not valid because of the reduced height of the slab.

If around the connexion supplementary reinforcement has been provided to prevent the punching phenomena the crack appeared next to the column. That shows that the connexion had an improved moment resisting behaviour.

For the flat slab structures one should keep in mind that once the plastic hinges are formed the punching danger appears, that is why the energy should be dissipated by other mechanisms.

Damages of the beams from torsion and bending

During the alternate cycles important cracks were noticed in the longitudinal and transversal beams (beams that were the equivalent of the slab strips).

Important cracks appeared in the transversal beams because of the torsion moments. These phenomena appeared due to the anchorage of the longitudinal reinforcement of the longitudinal beams in the transversal beam as well as because the active width of the slab is bigger than the one of the slab. This thing more obvious into the case of a flat slab where there are no distinct beams. The strip width is always greater than the column.

That is why the use of perimetral beams and of the structural walls is good for the flat slab structures. These structural elements will increase the structural rigidity and together with it the damages due to torsion.

Structural layout of flat slab structures in seismic areas

Flat slab structures are more flexible than the frame ones that is why the use of vertical elements such as structural walls is recommended in order to undertake the seismic forces.

As shown in the experiment and in the recent studies the slabs have a reduced capacity of energy dissipation, energy dissipation that takes place within the active area of the slab around the column.

Still some of the columns bases plastified, that means that the energy was dissipated in these sections.

Considering the above the Romanian code for flat slab structures limits the use of column-slab system to 2 level for seismic areas with the relative ground acceleration $a_g \leq 0,12g$ and an upper value for the reduction factor q=2.5.

For structures located in seismic areas with $a_g \geq 0,16g$ the use of the structural walls is mandatory, the value of the reduction factor „q" is taken according to the structural system. Perimetral beams must be provided in order to dissipate energy and also to ensure a better anchorage for the reinforcement.

The flat slabs are sensitive to seismic actions having as result damages from torsion and bending.

The Romanian standard does not allow the use of bent bars in the critical perimeter; instead the shear force must be taken by vertical bars.

For the seismic areas it is not recommended to have slab-column connexion without „sewing" reinforcement. Presstressing of the slab can improve the behaviour of the slab in this point, it introduces an inverted effect. All structural elements will have a reduced rigidity.

4. EXPERIMENTAL STUDIES AND CASE OF STUDY

4.1. Parametric study for a flat slab structure located in a seismic area

For the parametric study a structure having the following characteristics has been chosen:

- plan rectangular shape: longitudinal direction 3 spans L=6.50 m, transversal direction 5 spans, t =6.50 m
- height S+P+4E
- storey height He = 3,60 m
- cast in place reinforced concrete structure with flat slabs: concrete C20/25, reinforcement PC 52, PC 60, B 500 (C)
- the reinforced concrete columns have the following dimensions: 60x60 cm central columns, 45x45 cm corner and edge columns
- the 30 cm reinforced concrete shear walls were arranged on the perimeter of the structure
- the reinforced concrete structure has a thickness of 22 cm
- according to the seismic code P100/2006-1 the importance class of the structure is γ_1 = 1, class III

Te scope of the study is to determine the importance of the seismic vertical component for the punching computation of a flat slab. The punching phenomenon has been discussed in the previous chapters, but mainly for the gravitational loads without considering the seismic component. For the computation of the seismic vertical component was used the Romanian code P100/2006-1.

The table contains the control period and relative ground accelerations according to the Romanian code.

Control period T_c	Peak values of the design acceleration for an earthquake having a return period of 100 years
0,70 sec	0,08 g
	0,12 g
	0,16 g
	0,20 g
	0,24 g

1,00 sec	0,16 g
	0,20 g
	0,24 g
	0,32 g
1,6 sec	0,24 g
	0,32 g

The spectra used had a critical dumping of 5% ($\xi = 0,05$).

The code P100 provides the following formula for the computation of the seismic vertical component:

$$S_{ve(T)} = a_{vg} \times \beta_{v(T)}$$

$$a_{vg} = 0.7 \times a_g$$

$$T_{Bv} < T \le T_{Cv} \Rightarrow \beta_{v(T)} = \beta_{0v} = 3.0$$

The design spectra was computed according to the formula bellow considering a reduction factor q=1.5.

$$S_{vd(T)} = a_{vg} \frac{\beta_{v(T)}}{q}$$

The structural models were developed by the use of the programs ETABS and SAFE. For the design of the seismic force two methods were used, both accepted in the international codes, the static equivalent force and the quadratic combination.

The sectional, E_cI_c, rigidity of the vertical element was reduced with a coefficient equal to 0.5, while for the flat slab the value of the coefficient was 0.3.

Two relevant types of connexions have been chosen, one for central column and slab and the second for an edge column and slab.

The results showed that the seismic component does not have a major influence upon the column slab connexion. Still the shear the force associated to the vertical seismic component, for a design acceleration $a_g = 0.32g$, can reach up to 30% of the gravitational load.

Combining the two components, seismic and reduced gravitational load one can say that the summation of the two can reach the same value as the gravitational design load. This is valid for areas having high ground design acceleration.

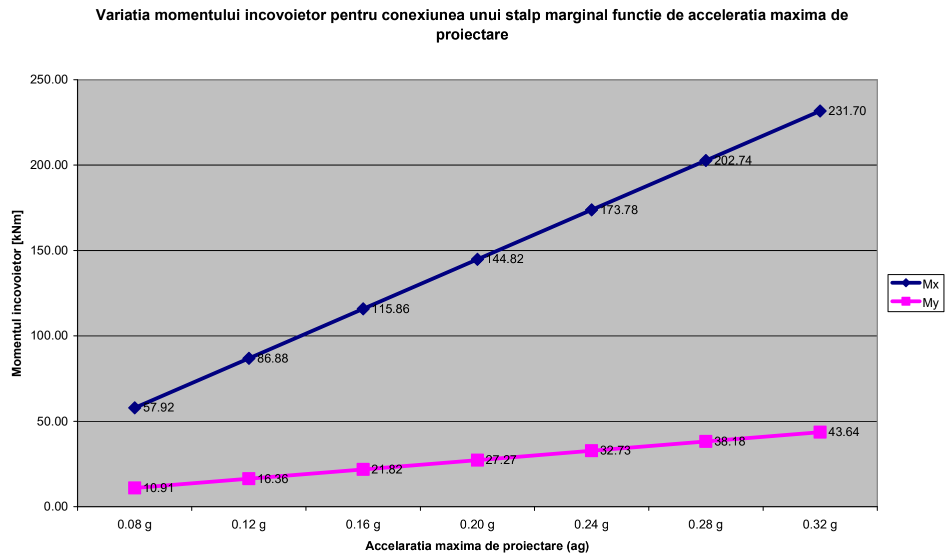


Fig.4.2 Variation of the bending moment for an edge column slab connection function of the design ground acceleration

It can be said that the design moment is directly proportional with the design ground acceleration. Thus for a for an a_g = 0,08 g, having a 50 kNm design moment, in the case of an ag = 0,32 g, the design value of the bending moment goes up more than 200 kNm.

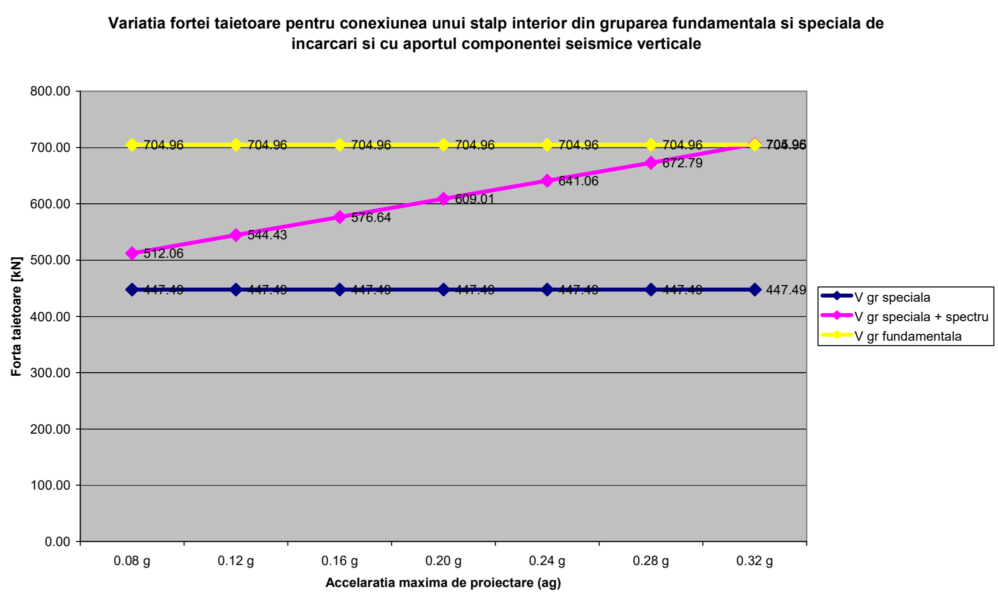


Fig.4.3 Variation of the shear force for an interior column slab connection for the fundamental gravitational load and the combination of the exceptional gravitational load summed with the seismic vertical component

The associated shear force increases with the design ground acceleration. In the case of the interior columns one can see that the summation of the seismic and exceptional gravitational load leads to the same value as for the design gravitational load. This is not valid any more in the case of the edge column slab connexion.

Even so for the punching check next to the column the capacity of the slab was not overrun for none of the above mentioned connexions, the value of the design effort being around 30% of the capacity.

As a conclusion it can be said that in the case of the interior columns connexion the summation of the seismic and exceptional gravitational has almost the same value as for the design gravitational load. This situation is not valid anymore for the perimetral column connexion, the value of the design gravity load being overrun.

4.2. Modelling of a flat slab for seismic and gravitational loads

In order to analyze the two forces acting simultaneously on the structure a computer program has been used, SAFE v.12.1.1. The slab above the 3rd floor has been chosen for analyse.

The sectional rigidities of the structural elements has been reduced according to the codes requirements as following, columns and walls 0.5, beams 0.4 and slabs 0.3.

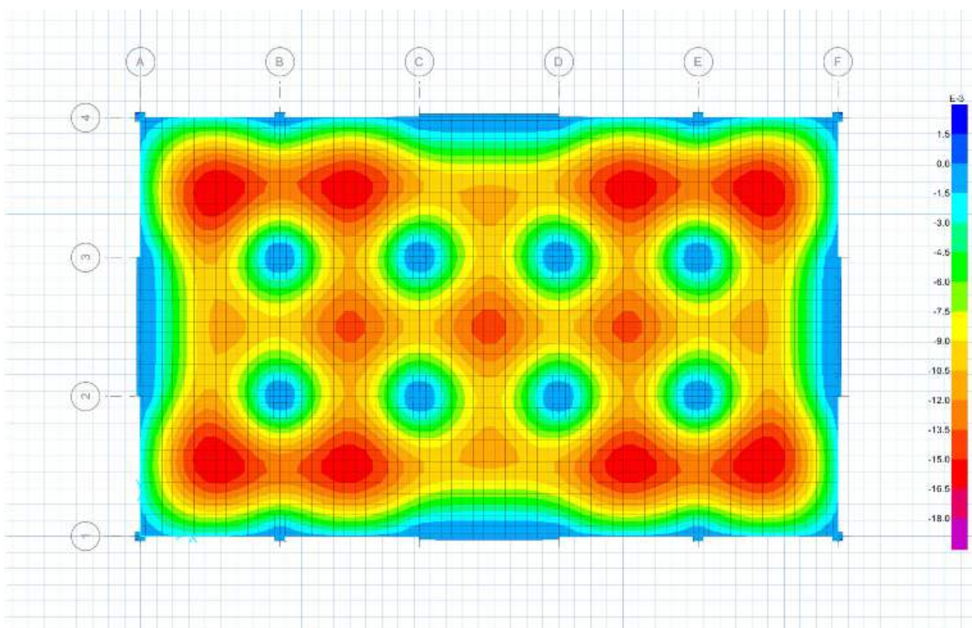


Fig. 4.10 Slab deformed shape for gravitational loads

The slab was subjected to gravitational loads in order to determine the following:

- Computation of the efforts by the finite elements method
- Dimensioning of an interior connexion

4.6. Conclusions, recommendations, research direction for reinforced concrete flat slab

The flat slabs do not have the same behaviour as the membrane slabs for seismic loads. Even though the less thick slabs that are considered to be working as a membrane have a certain rigidity and have shear forces perpendicular to their plan those are neglected compared with the values of the bending moments.

For the case of thicker slabs such as flat slabs this aspect can not be neglected anymore because the shear force has an important role for their dimensioning, especially for the column-slab connexion.

Comparing the design values for the seismic and the gravitational loads one can say that the values of the gravitational loads for the shear force are bigger than the ones for the seismic load. Generally speaking, the shear reinforcement used for the gravitational loads can cover the request from seismic loads as well; still for structures located in seismic areas with high loads a check is required.

The study of the column-slab connexion under cyclic loads (like the earthquake) considering the partial presstressing is an interesting one. The experimental study of this kind of connexion may lead to more ration solutions for computation the slab the reinforcement and an appropriate reinforcement design philosophy of the punching areas (critical areas).

5. CONCLUSIONS AND PERSONAL CONTRIBUTIONS

5.1 The advantages of the flat slab use in structures

As mentioned before the flat slab structures are an alternative for the modern structures. Their utility has been proven both form economical and practical point of view and in some cases the use of flat slabs comes out of technological reasons.

Some the above mentioned advantages are:

- reduced level height for civil structures
- easy placing of the formwork
- reduced erection time

Even though flat slab structure have some particularities that make them vulnerable to seismic actions and punching.

Chapter 4 contains a step by step analysis of the punching phenomena for the flat slabs. The design engineers should keep in mind that supplementary punching and „hanging" reinforcement should be provided. The last one is needed in order to provide the domino effect and the generalised collapse.

The use of presstresed concrete has some advantages because the amount of reinforcement used is reduced compared to the independent bar reinforcement. Also the shear force capacity around the supports is increased, the shear force being reduced by 0,8÷0,9 [29].

The pressterssing reinforcement can be pretensioned or posttensioned, with or without adherence. For the case of slabs, the use o pretensioned reinforcement is not a good alternative because it would require special formworks in order to allow the anchorage of the strands. That is why the use of posttensioned reinforcement is more rational.

The technological openings in the presstressed slabs are every difficult to be created afterwards, that is why the use the presstressing strips along the supports is preferred. The problem of the technological openings is an issue that has to be solved from the design stage. In the case when the presstressing was done on strips along the supports openings can be created more easily.

Another issue to be considered in the case of flat slabs is the fire protection.

The use of presstressed reinforced concrete slabs is an actual problem especially their behaviour in high seismic areas as well as for the punching phenomena. The designers should keep in mind that the use of presstressing reinforcement does not exclude the passive reinforcement, as mentioned in Chapter 3.

5.2 Specific requirements of flat slab structures located in seismic areas

The structures located in seismic areas have specific requirements from the general layout point of view and of the structural elements detailing.

A fundamental requirement is the energy dissipation, requirement that is covered by providing plastic hinges in the structural elements. Their position, computation and detailing have been discussed previously. The seismic base isolation can be successfully used for this kind of structures, but for their design a more elaborate design is needed.

If the frame or dual structures permit the distribution of the plastic hinges in columns, walls and beams the absence of beams obliges the engineers to use shear walls. Sever story drifts are also imposed. For areas having a design acceleration $a_g \geq 0{,}16g$ only one storey structures can be desingned without using shear walls.

The structural rigidity has a greater reduction coefficient in order to take in to account the crack of concrete under static and dynamic cyclic loads.

An “integrity” reinforcement has to be provided in order to prevent the floor collapse.

The vertical component of the seismic action should be considered because it increases the punching force and diminishes the presstressing advantages.

The rigid slab requirements can be easily obtained by the use of flat slabs. Their thickness (bigger than the membrane slabs) satisfies the in plane rigidity necessity.

5.3 Comparison between the presstressed flat slab and ordinary bars reinforced flat slabs

The economical rentability of presstressesd flat slabs is obvious especially for big spans; in the case of usual spans it is more expensive than the classic one. For spans over 7÷8 meters the use of presstressing becomes an economic solution bringing a 20% money saving.

The test showed a better behaviour of the prestressed concrete structures in the sense that the drift increased from 3‰ for non presstressed concrete flat slab structures to 5‰ for presstressed concrete flat slab structures.

The test for flat slab structures located in seismic areas are not numerous and do not cover all the structural aspects.

Regarding the slabs, the test did not manage yet to emphasise the behaviour under cyclic loads.

Design codes cover mainly the behaviour under gravitational loads.

5.4 Personal contributions

Out of the thesis „Behaviour of Prestressed Slab Floors for Structures Located in Seismic Areas" the following elements can be considered as personal contributions:

1. A synthetic analysis of the flat slab structures from the functional and structural point of view, considering the role of the slabs in the design of the structures located in areas having high seismic activity. The role of rigid slab is a very important one in the design of a structure.
2. A resume regarding the actual research stage both theoretical and experimental in the field of flat slabs and their design. The previous design concepts had considered only the gravitational effects that have been updated with the ones regarding the behaviour under seismic loads. These refer to the moment capacity of the column-slab connexion as well as the energy dissipation mechanism in flat slab structure.
3. Another subject that was developed is the behaviour of flat slab structures in seismic areas. The flat slab structures are known as being sensitive to seismic actions. A fundamental problem of this kind of structures is the energy dissipation that requires a certain structural layout. This layout includes the use of structural the walls and of the preimetral beams, that can reduce also the drift allowing them to fulfil the requirements of the actual codes. The tests are quite few, done in USA, Japan and Europe. Nevertheless, the economical advantages for such structures are not to be neglected.
4. During the experimental part of the thesis I have studied the influence of the vertical loads component upon the slab structures. Its a well know fact that the flat slabs are sensitive to the vertical loads, during the modelling of the structure I have emphasised the fact that in high seismic areas the exceptional loads brought an increase of 30% of the necessary shear force. The check of the shear capacity of the slabs was done according to the European code Eurocode 2, that is considered to be the closest to real behaviour.
5. For the future research I can think of the column-slab connexion for prestressed slabs subjected to alternative loads, energy dissipation trough the connexion and the future repairing options. This approach would reduce the reinforcement consumption and increase the ultimate displacement capacity.

The design of flat slab structures located in seismic areas is an actual problem both in Romania as well as for the rest of the world. Because of the extended use of such structures by the architects and developers because of reduced costs and reduced execution time the structural engineers have to realise complex projects from the structural layout and computation point of view. That is why such structures should be analysed very carefully because of their particularities compared to the classic structures.

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