Seismic Analysis and Design of NPP Structures: An Integrated Approach

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1 INTRODUCTION

Numerical methods for static and dynamic analysis of structures, as well as for the design of individual structural elements under the applied loads are under continuous development, being very sophisticated methods nowadays available for the engineering practice.

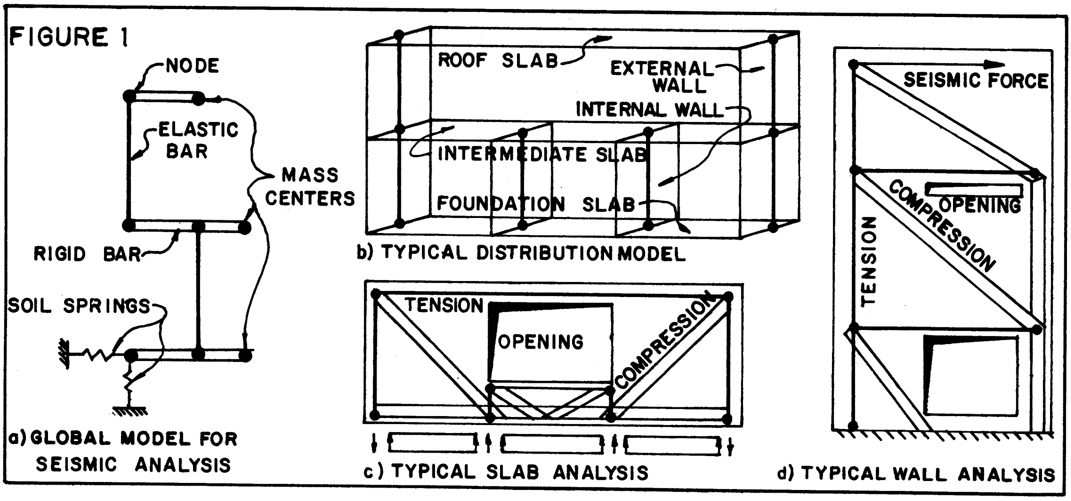
Nevertheless, this sophistication will be useless if some important aspects necessary to assure full compability between analysis and design are disregarded. Some of these aspects are discussed herein.

This paper intends to present an integrated approach for the seismic analysis and design of NPP structures: the development of models for the seismic analysis, the distribution of the global seismic forces among the seismic-resistant elements and the criteria for the design of the individual elements for combined static and dynamic forces are the main topics to be discussed herein. The proposed methodology is illustrated in Fig.1. Some examples taken from the project practice are presented for illustrating the exposed concepts.

2 GLOBAL MODELS FOR THE SEISMIC ANALYSIS

The complete dynamic analysis of structural systems possessing a very large number of degrees of freedom demands a computational effort still prohibitive for the current project practice. In this way, the mathematical models used in the seismic analysis of structures are, in general, much less refined than the models to be adopted in the static analysis. Some general qualitative aspects support the adoption of coarser models in the dynamic analysis (Wolf,1985): seismic loads excite, generally, only some of the lowest structural frequencies; incertainties involved in the evaluation of the seismic loads are normally larger than for the static ones; it is generally necessary a number of degrees of freedom to represent the inertial forces much smaller than for representing accurately the static ones.

There are several methods for reducing the number of degrees of freedom for the dynamic model from an existent model for the static analysis (mass lumping followed by static condensation, substructure-mode synthesis, etc.). Nevertheless, the current practice, specially for box-type structures, is to develop directly the models from the geometric properties of the buildings.
The so called "stick models" (as sketched in Fig.1a) are largely used for modeling NPP structures, specially the rigid-box type ones. In these models, the stiffness of walls between two consecutive floors is condensed in a single beam.



The entire masses (rotational and translational) assigned to each floor are condensed in an unique node. Soil impedance functions are considered in the node representing the geometric center of the foundation slab.

A special concern shall be present when modeling the structures: the dynamic forces to be absorbed by each structural element shall be in accordance with the effective capacity of the elements in resisting these forces when performing their structural design. The main effect to be considered in the modeling is the loss of rigidity of walls and slabs due to the several openings usually present in them; it is recommended that only the parts of the structural elements effectively considered in the design should be accounted for when determining the geometric properties for the model. The consideration of the slabs of a floor as infinitely rigid diaphragms shall be preceded by a careful analysis.

3 DISTRIBUTION OF THE GLOBAL SEISMIC FORCES

For the design of the seismic-resistant structural elements, the forces evaluated in the global seismic analysis shall be distributed among them. For this, special models shall be developed.

Depending upon the characteristics of the analysed structure, very large finite element models can be used for the distribution of the global seismic forces. For instance, in the design of the Angra 2 NPP Reactor Building, very complete and sophisticated models were used (Diaz et al, 1987).

For the box-type structures usually found in NPP, special distribution models can be adopted (as sketched in Fig. 1b). In these models, all the seismic-resistant elements shall be individually represented. The walls are represented by beams of vertical axis, fixed in the foundation slab. The walls are linked, in each elevation, by elastic (or rigid) beams representing the in-plane stiffness of the slabs. Seismic forces are considered through distributed loads, applied in the regions where they effectivelly occur. Special care shall be taken with the reduction in the stiffness due to the openings usually present in the structural elements.

The distribution models are the bridge between the seismic analysis and the design of the resistant elements; they shall assure the compability throughout the entire design process.

4 DESIGN AND DETAILING OF STRUCTURAL ELEMENTS

In the box-type structures usually found in NPP, the seismic resistance is mainly assured by an assemblage of horizontal (slabs) and vertical (walls) bidimensional structural elements. These elements don't possess, in general, one of their dimensions preponderant with relation to the remaining ones. Besides this, they usually present a great number of important openings. Therefore, the current criteria for flexural and shear design of beams are, in general, inapplicable.

The design of reinforced concrete walls and slabs in the herein presented methodology is based on the strut-and-tie models (Schlaich et al, 1987), extended for the resistance to seismic loadings.

The design with these models is based on the analysis of pre-defined plane trusses, where the struts represent the compressive stress fields in the concrete, and the ties, the reinforcing bars. The design process consists in: determination, through static equilibrium, of the forces in the elements of the truss; check of compressive stresses in the concrete, from the determined values of the compressive forces; design of the reinforcement, from the values of the tensile forces in the truss. The detailing of the reinforcement follows directly and shall be in accordance with the adopted resistant truss model.

Two main criteria are suggested for the conception of the resistant trusses: the geometry shall follow the elastic stress fields; the designed reinforcement in bidimensional elements shall be as uniform as possible.

5 EXAMPLES

In Figs.2, the application of strut-and-tie models, in elementary situations is shown. Figs. 2a,b show resistant schemes for shear walls without openings and Figs. 2c,d,e, schemes for walls with openings. These figures show the adopted reinforcements, dimensions, resistant truss models, the ultimate resistant horizontal forces and total steel spent in each situation.

Figs. 2,a,b, show two different possibilities for resisting the horizontal loads in walls without openings. In Fig. 2a the total resistance is provided by uniformly distributed reinforcement; in Fig 2b part of the resistance is given by concentrated reinforcement in the extremities. In this particular analysed situation, for resisting the same horizontal force, the steel spent in Fig 2b is 11% greater than in Fig 2a.

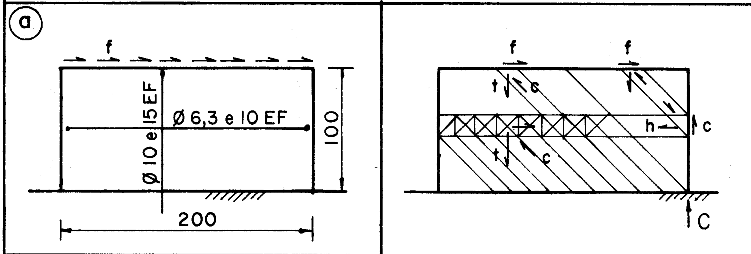
In Fig 2c, the same vertical reinforcement of Fig.2a is placed in a wall with opening. Due to the opening, the horizontal reinforcement is increased for assuring the transferring of horizontal forces h1,h2,h3 to the right side of the wall. In despite of the reinforcement increase, the resisted horizontal force decreases in 50%. For resisting the horizontal forces of Figs 2a,b, the total reinforcement shall be increased, as shown in Fig.2d.

The influence of the direction of the applied force is analysed in Fig 2e. Since the position of the opening is more favourable for the direction depicted in this figure, less reinforcement is placed, comparing with Fig 2c, but the resisted force is 24% greater.

Figs 3 and 4 show examples of design of a shear wall and a slab taken from the actual project practice.

WALL THICKNESS: 12cm; STEEL REINFORCEMENT: f_y = 500 MPa ; CONCRETE: f_{ck} = 15 MPa	ULTIMATE LOAD: F_u STEEL SPENT : s

(a)

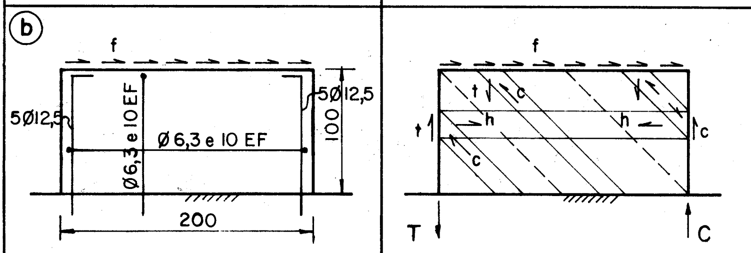


f_u = 315 kN/m

$F_u = f_u x \ell$ = 315x2,0=630 kN

s = 27,2 kg

(b)

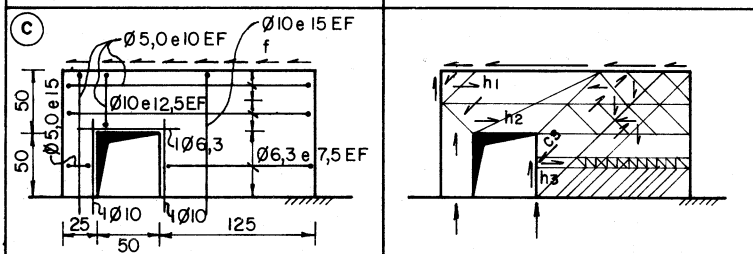


f_u = 315 kN/m

$F_u = f_u x \ell$ = 630 kN

s = 30,2 kg

(c)

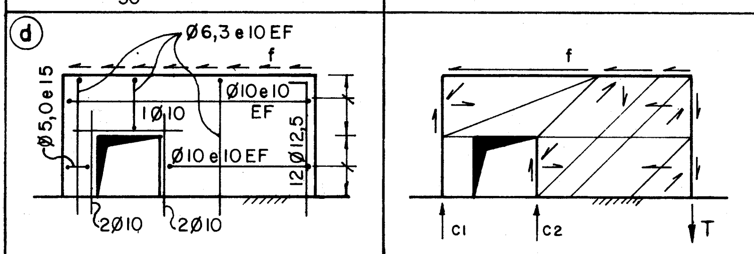


f_u = 160 kN/m

F_u = 160 x 2,0 = 320 kN

s = 21,7 kg

(d)

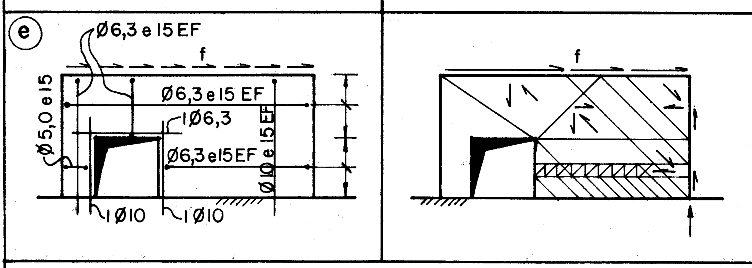


f_u = 315 kN/m

F_u = 315 x2,0=630 kN

s = 41,0 kg

(e)



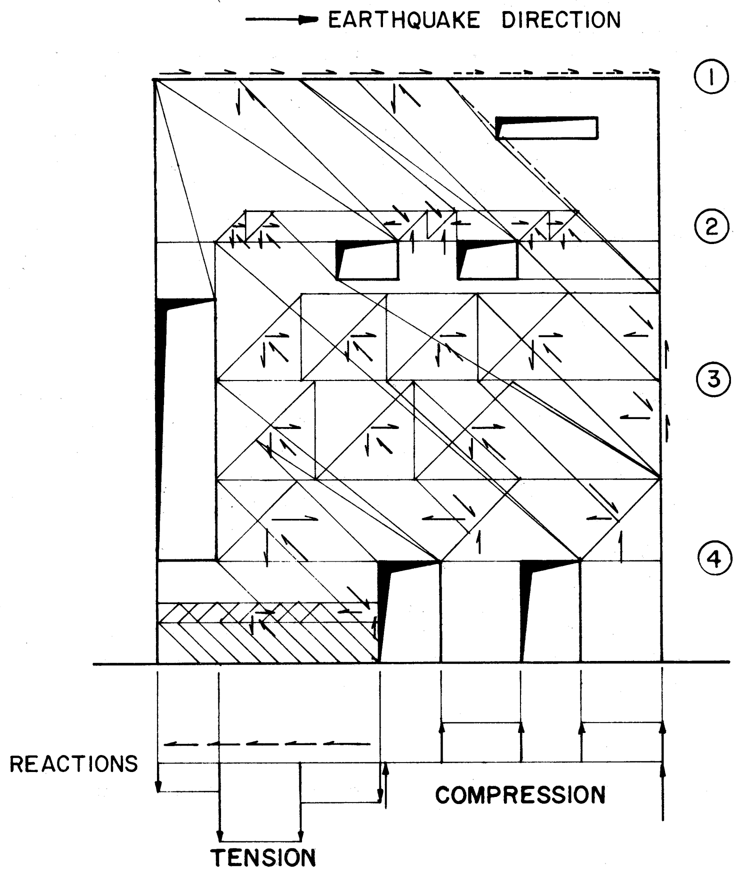
f_u = 198 kN/m

F_u = 198 x 2,0 = 396 kN

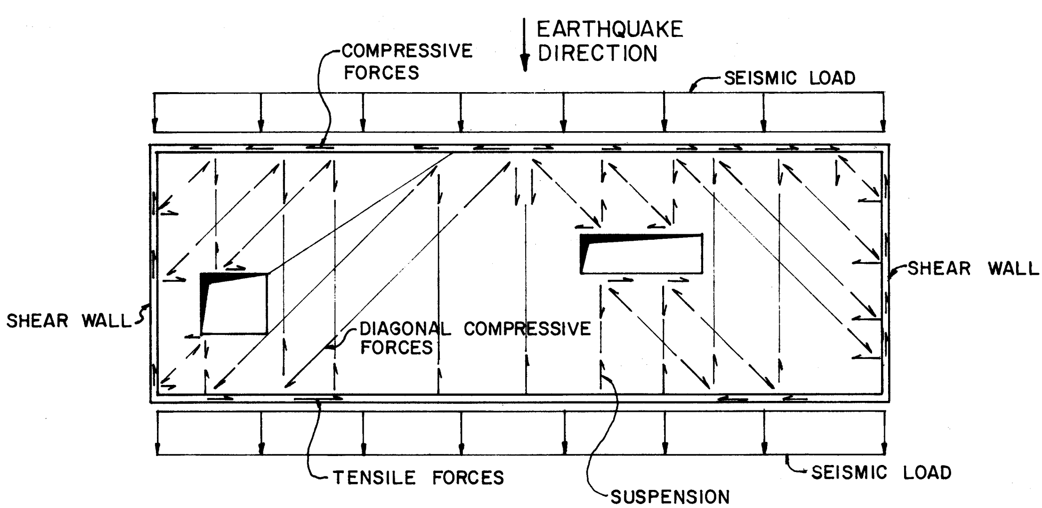
s = 17,4 kg

NOTE: DIMENSIONS IN CENTIMETER

FIGURE 2



SHEAR WALL FIGURE 3



SLAB FIGURE 4

The shear wall in Fig.3 is subjected to horizontal forces transmitted by the slabs of the superior floor 1. Part of these loads shall be transferred to the left side of the floor (dashed arrows). Equilibrium is found in floor 1 with tension ties linked in the foundation slab and diagonal struts linked in floors 2 and 3. Due to the openings in floor 2, equilibrium is found in the resistant parts in left and right sides (tension ties) and between (compression struts) openings with diagonal struts linked in floors 3 and 4. Near level 3 equilibrium is found between compression forces concentrated in the right extremity of the wall and tension ties which transfer horizontal forces again to the left side of the wall, where they found equilibrium with tension ties linked in the foundation and diagonal struts linked in floor 4. Due to the openings in floor 4, the entire horizontal force is transferred to the resistant part in the left side of the wall; compression is absorved in the two parts in the right side of the wall.

The slab in Fig.4 is subjected to inertial forces (slab masses times horizontal acceleration) and shall transfer these forces to the shear walls in the proportion indicated in the distribution analysis. The reinforcement of the slab shall assure the resistance to the internal tension forces; the resistance scheme shall accordingly consider the presence of the openings in the slab.

6 CONCLUSION

An integrated approach for the seismic design of NPP structures was presented. In this approach, full compability between analysis and design is assured by the distribution models and through the reinforced concrete design based on strut-and-tie models, as shown through numerical examples.

7 REFERENCES

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