

ANALYSIS OF MULTI-STORY BEARING WALL STRUCTURES

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SYNOPSIS

Developments achieved in the field of analysis of multi-story structures are presented. Some basic relations referring to the evaluation of seismic effects and to substructure techniques are given. The software used for numerical analysis is reviewed. Some types of investigated structures are described and results are reviewed. Photo-elastic stress analysis is presented too. Comparison of results obtained by means of various techniques is discussed.

1. INTRODUCTION

Two design institutes had recently to work out designs of tall residential buildings intended for series construction. The Building Research Institute (INCERC), Bucharest, has been requested to carry out the analysis of seismic effects, under following conditions:

- a- determination of conventional effects on the basis of modal analysis;
- b- use of computers.

Three basic types of bearing wall structures (with some variants) have been analyzed by means of finite element techniques. This analysis, which is briefly presented, has been based on a software elaborated in the institute [3] and on an appropriate stochastic approach of the seismic analysis [2]. Results obtained from numerical analysis were confirmed by photo-elastic analysis performed for the same structures. Data on natural periods and shapes were confirmed also by full-scale experimental data [4], [5].

2. BASIC RELATIONS

The Romanian aseismic design code requires for design of tall structures an estimate of seismic effects on the basis of modal analysis. Relations used in current practice have been modified having in view two aspects:

- a. Determination not of conventional seismic forces, but of equivalent displacements, which are a more convenient startpoint for automated stress analysis and for consideration of the coupled deformation of different bearing elements.

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b. Possibility of introducing explicitly some characteristics of the ground motion which are currently neglected by codes (three-dimensional motion, non-synchronous motion at different ground-structure contact points).

The basic relation adopted, derived from the developments of [2], is

$$u_{ir}^{conv.}(x_k) = \frac{k_s g}{\omega_r^2} \delta_{ir}(x_k) \quad (2.1)$$

(g : gravitational acceleration; k_s : fraction of g considered for design; ω_r : natural circular frequency of order r), where the non-dimensional factor $\delta_{ir}(x_k)$ is

$$\delta_{ir}(x_k) = v_{ir}(x_k) D_r \quad (2.2)$$

($v_{ir}(x_k)$: normalized natural shape of order r , at the point x_k , on the direction i), where the participation factor has an expression derived in [2],

$$D_r = \frac{1}{\omega_r^2} \sqrt{\sum_{a,b}^{1,m} Q_{ar}^o Q_{br}^o F_{abr}^o [w_g; o]} \quad (2.3)$$

(Q_{ar}^o : amplitude of force applied to the ground, corresponding to oscillations of amplitudes $v_{ir}(x_k)$ and of circular frequency ω_r , in case of an ideally elastic material; $F_{abr}^o [w_g; o]$: a correlation tensor). For practical purposes the expression (2.3) has been replaced by the expression

$$D_r = \frac{1}{\omega_r^2} \beta(T_r, n_r) \sqrt{\sum_{a,b}^{1,m} Q_{ar}^o Q_{br}^o k_{ab}} \quad (2.4)$$

($\beta(T_r, n_r)$: a dynamic factor, determined according to code provisions; k_{ab} : a correlation tensor which permits introduction of assumptions on direction of motion and on correlation between different components $u_{ga}(t)$ of the ground motion, corresponding to the various degrees of freedom, a , of the contact zone).

The analysis of structural behavior has been performed by means of numerical methods, based on the use of finite elements for bearing walls. This approach leads to several thousand nodes for a multi-story structure. This fact has led to the use of sub-structures and of condensation techniques.

The behavior of a structure or of a sub-structure is characterized basically by an N_1 -dimensional displacement vector U . The N_1 degrees of freedom can be separated into two categories: N_e external,

and N_i internal degrees of freedom. The vector U can be arranged in the form

$$U^T = [U_e^T, U_i^T] \quad (2.5)$$

which leads to a corresponding representation of the stiffness matrix A_K ,

$$A_K = \begin{bmatrix} A_{ee} & A_{ei} \\ A_{ie} & A_{ii} \end{bmatrix} \quad (2.6)$$

The condensed N_e -dimensional stiffness matrix will be

$$A_{K \text{ cond.}} = A_{ee} - A_{ei} A_{ii}^{-1} A_{ie} \quad (2.7)$$

and the values of the components U_i will be

$$U_i = - A_{ii}^{-1} A_{ie} U_e \quad (2.8)$$

The corresponding inertia matrix has been generally evaluated on the basis of equivalent lumped masses. The eigen-value problem for a condensed system once solved, the natural periods T_r and the natural shapes U_r are available, and displacements U_{ir} , stresses, and forces Q_{ar}^o can be determined starting from relation (2.8). Sub-structures dealt with can represent a plane bearing wall, a plane frame, a one-story fragment of a bearing wall, a couple of such fragments, etc.

The main computation steps to be performed are:

- determination of stiffness matrices A_K for sub-structures dealt with;
- determination of condensed matrices $A_{K \text{ cond.}}$ and of influence matrices $- A_{ii}^{-1} A_{ie}$;
- determination of matrices and solution of eigen-value problem for the whole structure (including displacements U_i , stresses, and forces Q_{ar}^o);
- determination of participation factors D_r and evaluation of conventional effects (displacements $u_{ir}^{\text{conv.}}$ (x_k), stresses, etc.).

These computation steps can be applied in case of sub-structures corresponding to a whole bearing element, or to parts of it. Condensed flow charts are given in fig. 1 and fig. 2 for both variants, which have been actually adopted for programming computations.

3. PROGRAMMING

The programs, worked out in two variants, corresponding to the flow charts of fig. 1 and 2 respectively, have been based on a software designed to cover various problems of structural analysis for various types of structures [3]. The models of constitutive elements used in this view have been:

- a. a model of two-end members (considering axial, bending, and shear deformation);
- b. a model of McLeod finite element (rectangular element with three degrees of freedom per node: two translation, and one rotation displacement; rotations are defined alternatively for horizontal and vertical elementary segments).

The system of general-purpose subroutines for analysis of structural behavior have permitted without any notable difficulty assembling, condensation, solving of eigen-value problems, evaluate of participation factors, etc.

4. STRUCTURES DEALT WITH. RESULTS OBTAINED

Three types of structures have been dealt with by means of computational techniques presented above:

- a. a twelve-story bearing wall structure (the current floor is represented in fig. 3; the lower two floors are slightly different);
 - b. an eighteen-story composite structure (the current floor is represented in fig. 4);
 - c. a twenty-four composite structure (the current floor is represented in fig. 5; the basement floor is slightly different).
- The types mentioned above included some slightly different variants.

Computations included primarily the determination of three lower natural modes for each flexional (in transverse and longitudinal direction) and torsional type of deformation. The structures a and b have been thus analyzed by means of 9 natural modes, while the structure c, with a practically square floor, has been analyzed by means of 6 natural modes. The natural shapes of the structure c are given in fig. 6. The natural shapes of the structure a are given in [1], where they have been used as a basis for the analysis of torsional oscillations.

The normal modes permitted to determine participation factors and, thereafter, conventional displacements and stresses.

Some stress diagrams are given in fig. 7. They correspond to the lower horizontal section of the bearing wall of the structure c, and represent normal stresses for the two lower order translation modes.

A distribution of shear forces in the horizontal members of the bearing wall of the same structure, for the three translation modes which have been determined, is given in fig. 8.

5. PHOTO-ELASTIC ANALYSIS

A photo-elastic stress analysis has been simultaneously performed for some bearing walls. Several variants have been dealt with in view of analyzing the influence of the various types of openings at the lower levels on the stress distribution. The variants dealt with have permitted the design engineers to adopt favorable structural solutions. The general photo-elastic picture has been useful also for the division of bearing walls into finite elements.

The optic sensitivity of the material used has been satisfactory: $S = 7.4$ kgf./cm*band order in natrium light. Transparency technique and compensation (Tardy) procedures have been used.

The final results included stress diagrams and evaluation of shear forces in horizontal members. Photo-elastic results have been in good agreement with computatibanal results. The general photo-elastic picture has been interesting for evaluating structural performance even beyond determination of stress diagrams.

Some typical results obtained by this tool are presented in fig. 9 and 10. In fig. 9 a bearing wall and its loading scheme are given. A diagram of normal stresses at the vertical edge is represented on left side. A diagram of shear forces in the horizontal members of the bearing wall is given in fig. 10.

6. FINAL REMARKS

The experience of automated numerical analysis of seismic behavior of tall buildings by means of finite element techniques has been encouraging. This approach will be used therefore more extensively in future. The investigation by means of automated numerical, and of photo-elastic analysis used for the same structure appeared to be reasonable too.

The main shortcomings met in this work are due to the fact that some steps are not yet automated. This refers to the determination of initial data for finite element analysis as well as for the interpretation of final results. Efforts should be done therefore in future for an automated division into finite elements and, eventually, into sub-structures, as well as for using graph plotter techniques.

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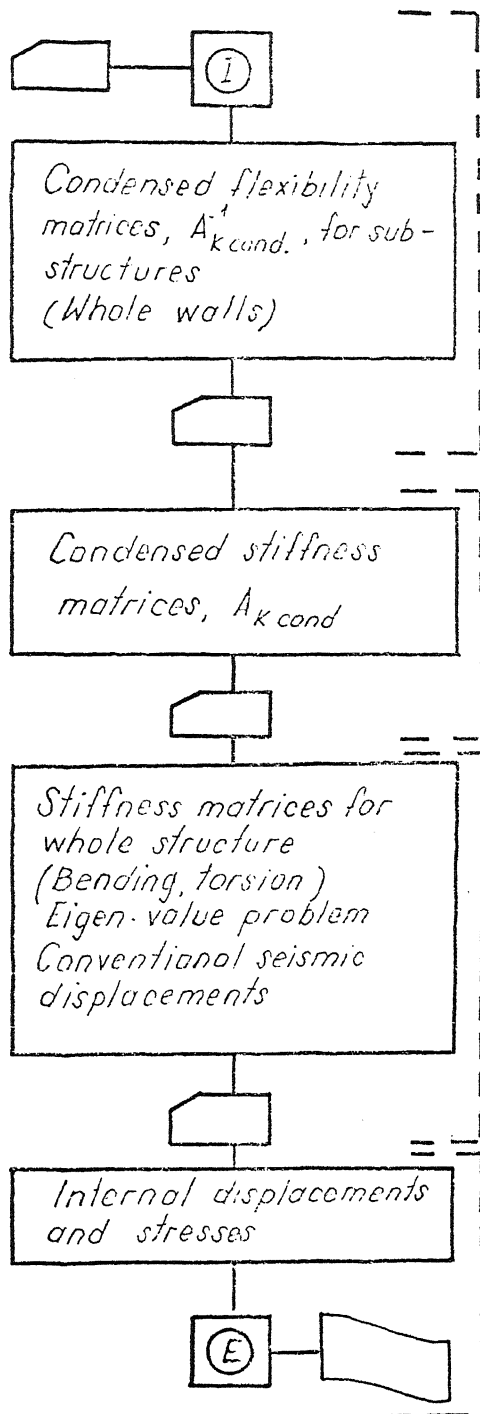


Fig. 1

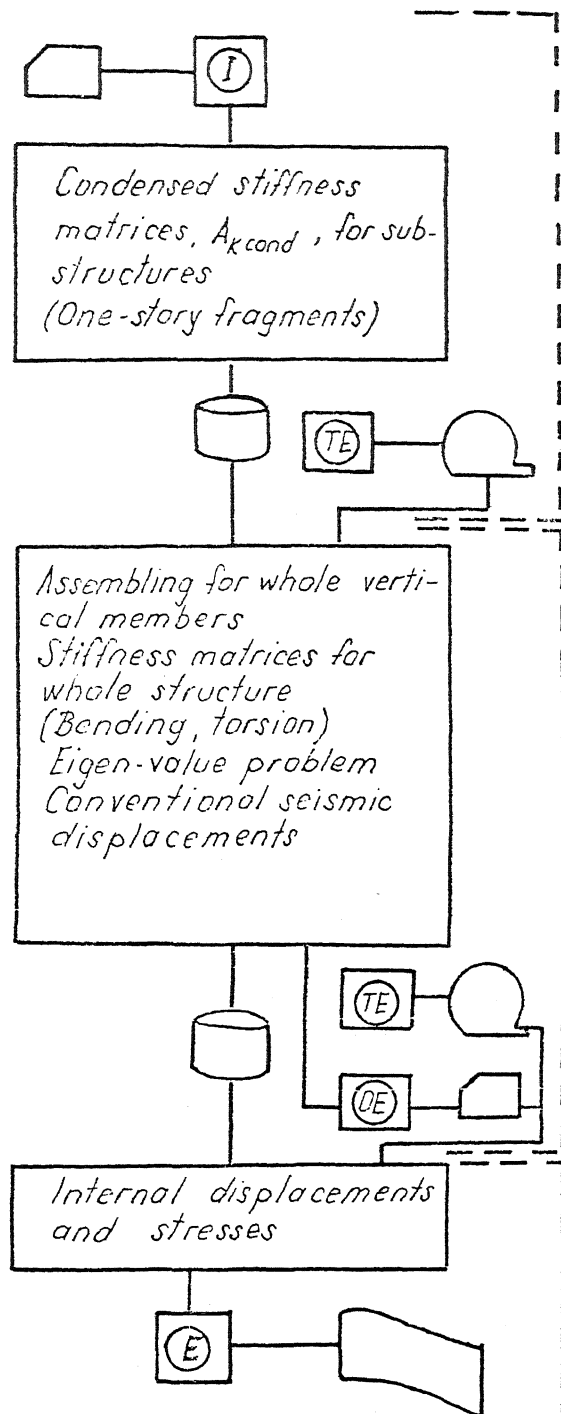
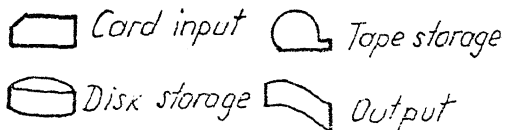
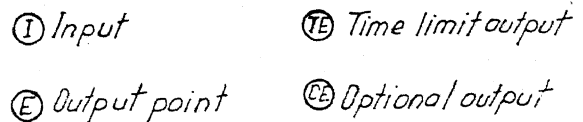


Fig. 2



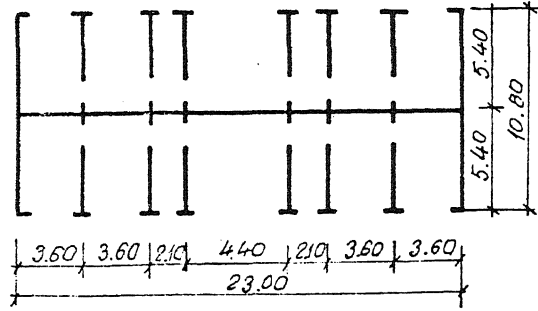


Fig.3

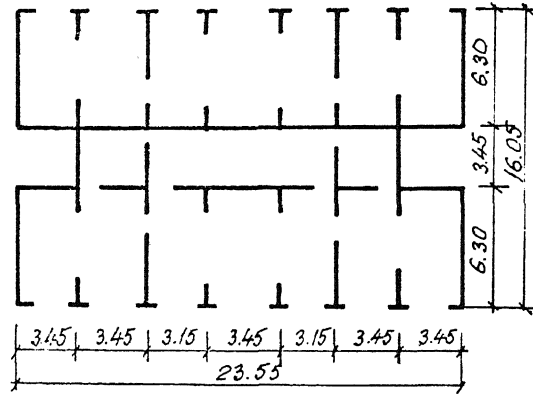


Fig.4

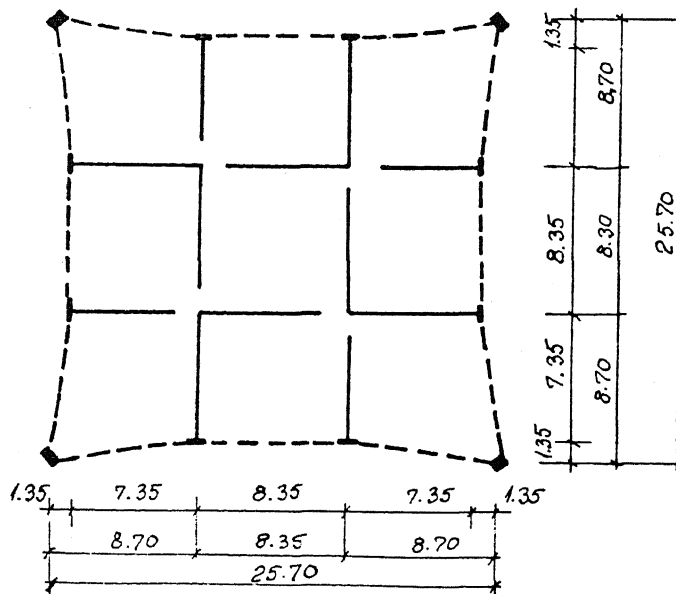


Fig.5

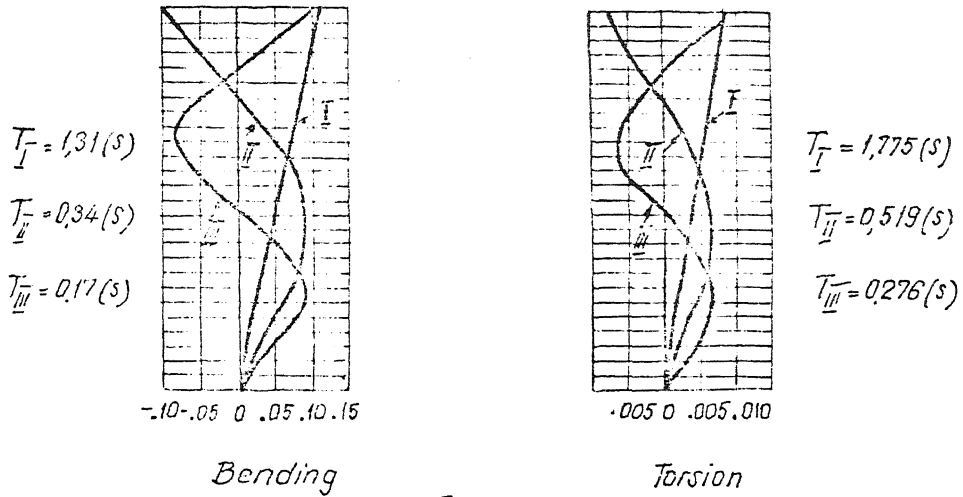


Fig. 6

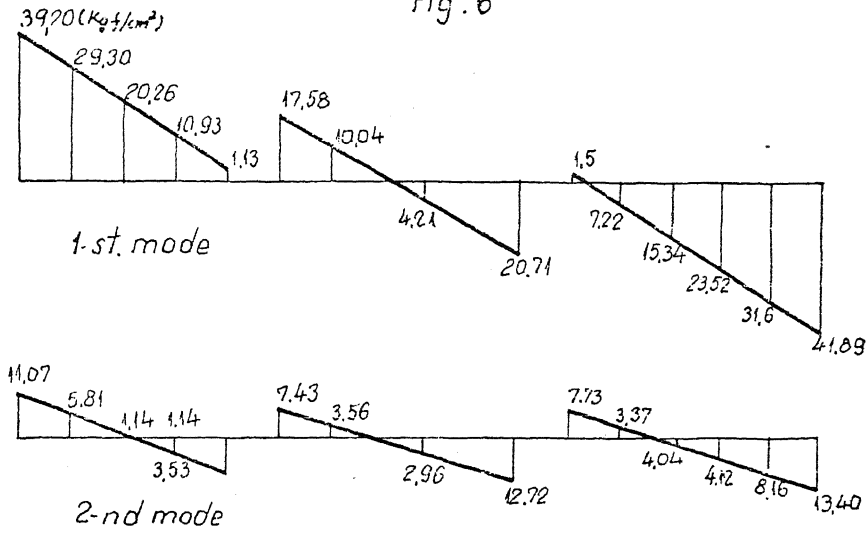


Fig. 7

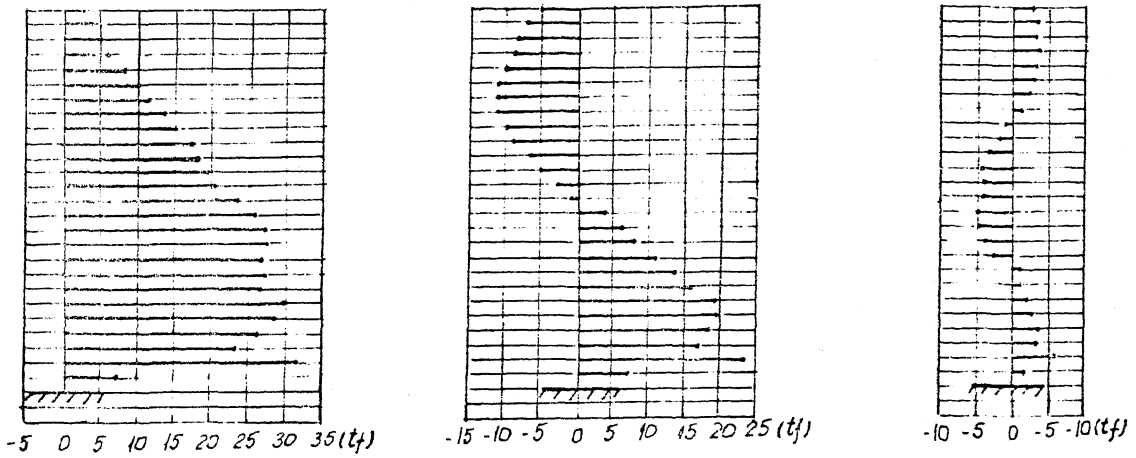


Fig. 8

