COMPUTER-AIDED STRUCTURAL DESIGN OF PRECAST REINFORCED CONCRETE BUILDINGS

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(Received: March 28, 1983)
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1. Introduction

Computer technology has developed rapidly since its initial use in engineering. The operation speed and storage capacity have significantly increased alongside with a drop of prices and sizes. Terminals directly connect the user with larger computers, or high-capacity microcomputers may be used at one's own working place. Digitalizers permit to input, beside numerical data, also graphic ones to the computer, yielding, in turn, also graphic outputs through plotters. The graphic display appliances are of especially great importance, offering the designer an interactive use of the computer with the possibility of direct data input and output.

Also programming possibilities improved considerably. High-level programming languages, well adapted to technical terms, as well as problem-oriented languages and program systems assisting the different specialities are now available. Random access backing stores called forth rapid handling of data bases and data banks containing a wealth of numerical and verbal data; special data management systems have been developed for them, just as methods for selecting optimum design variables.

These possibilities have brought about a qualitative change in the use of computers for engineering design (including structural design). At the beginning, computers were applied only for some work-absorbing parts of calculations, whereas today increasingly complex parts of the planning process are accessible to automation; thus "computer-aided design" or "automated design" can be spoken of. The designer can direct the computer to work out numerous design alternatives and he may chose — partly by means of the computer — the most suitable among them. The conception part of the design and the final decision are of course incumbent on man, but — especially in case of the above-mentioned interactive design — the computer may still be of great help also in this design phase.

Computer-aided design may be especially efficient for the design of buildings of precast units in system-building with specifications going into particulars where C. A. D. may become sub-system of the system building design process.

2. Building System "BVM-TIP"

In 1977 the Concrete and Reinforced Concrete Works (BVM) purchased the know-how of the Swedish firm AB STRÄNGBETONG; and on the basis of this the Institute for Design Development and System Design has developed

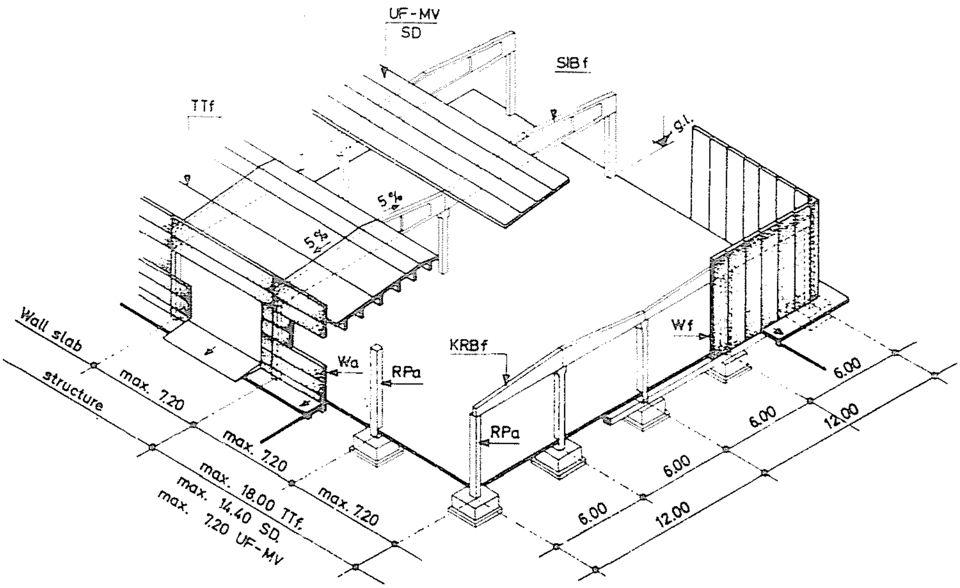

Fig. 1. Single-storey frame system "BVM-TIP"

a new, integrated building system "BVM-TIP". This system is suitable to erect single or multistorey r.c. framed buildings for industrial, agricultural, commercial or other uses. The frame system of the buildings consists of precast r.c. columns and precast, prestressed r.c. beams. The floors may be produced of either of three different kinds of prestressed r.c. units: SPAN-DECK floor slabs, round-hole floor slabs type UF-MV or roof floor slabs with TT section. The façades can be formed of vertical (standing or suspended) or horizontal, heat insulated r.c. wall panels.

The single-storey frames may be constructed with or without a travelling crane, with large-span transversal girders or short longitudinal girders; latter with sloping girders and parallel-flange roof slabs (Fig. 1) or with girders of constant height and sloping roof slabs. The structural model consists of columns fixed at the bottom and connected on the top with hinged beams.

Variants of multi-storey buildings: the beams are supported on the columns by r.c. cantilevers or concealed steel cantilevers (Fig. 2). The structural model is a chain of hinged bars; spatial stiffness of the building is provided by shear walls.

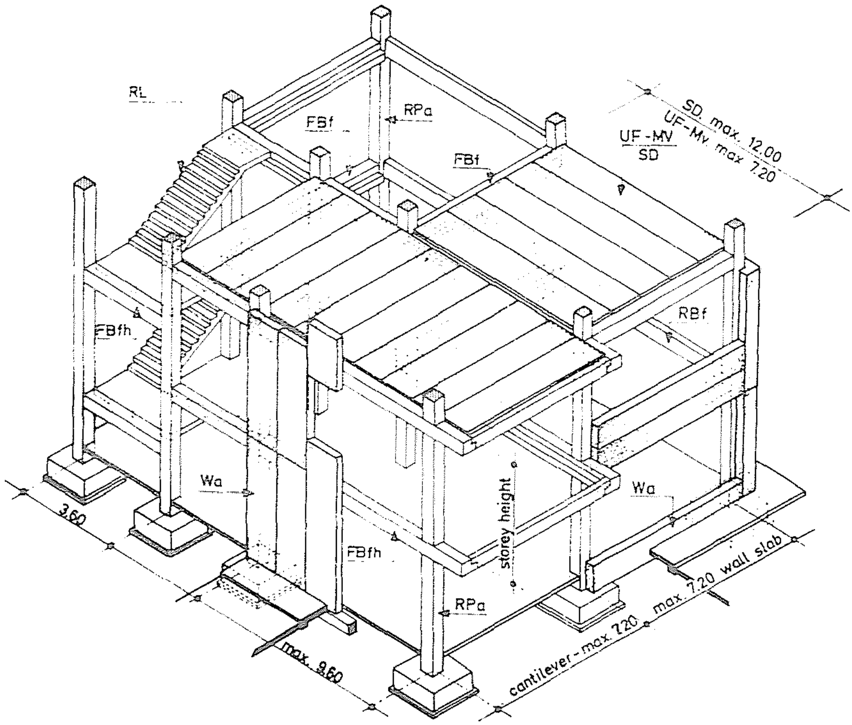

Fig. 2. Multi-storey frame system "BVM-TIP"

On commission by the Institute for Design Development and System Design, a team of the Department of Strength of Materials and Structures, Technical University, Budapest, developed from 1977 to 1981 the *intergrated computer system for the structural design* of the above-mentioned building system. This program system is discussed in the following as a realized example of "computer-aided design".

3. Purpose and tasks of the program system

Purpose of the program system: a maximum of computer aid of the structural design of "BVM-TIP" framed buildings of optional ground plan and optional number of storeys, based on the simplest possible designer input. To this purpose the program system accomplishes the following *tasks*:

— Based on data given by the designer it produces the so-called *internal image* of the construction, i.e. it numbers the columns, distributes the floor slabs, disposes and numbers the floor beams.
— Traces on the plotter preliminary floor plans on which the designer can check the correctness of the input data and of the internal image.

— Calculates the *loads* of the structural members (floor slabs, beams, columns, shear walls) and the *design values of internal forces*; produces *combinations of design values of internal forces* significant for checking the load-bearing capacity.
— *Selects* precast structural units (floor slabs, beams, columns) from the data base of system components according to the designer's whishes so as to meet geometry, strength and deformation conditions.
— Prepares the *schedule* of system components.
— Traces on the plotter the *floor plans* for each storey, in two phases (the column/beam plan and the floor slab layout plan).

4. Possibilities and limits of use

The structural design of any building which can be constructed in the BVM-TIP system can be carried out with the structural design program system (with a few exceptions). In the case of single-storey buildings, the building may be with or without a craneway, the ground plan can be of rectangular, L, T or I shape. In case of multi-storey buildings, they should fit a rectangular grid with optional ground plan and contour. The building may have interior courtyards, floor holes and set-back parts, and cantilevers as well. The higher storeys can be set back as compared to the lower ones. Also the storey heights may be different.

Any *load* occurring in practice may be defined on the structures. Beside the uniformly distributed floor loads, the loads due to façade cladding and crane loads, also loads distributed over any rectangular surface and linear or concentrated loads may be specified. The wind load needs not figure in the input as the computer takes it automatically into account, according to standard specifications. The effects due to temperature changes, shrinkage and placing inaccuracies are also automatically involved in the program.

Limits of application of the program system are irrelevant in general to the design of a building in practice. Some limitations: the number of storeys cannot exceed 10, and a maximum of 200 columns can be designed.

5. The input system

In developing the input system it has been endeavoured to enable the designer to specify the building and its loads with the smallest amount of input data and paper work possible. On the nine different data sheets the data to be specified are divided into three principal groups:
— some general data concerning the building;

— principal geometric data of the structural system (storey heights, column layout);
— loads acting on the building.

Specification of the *column system* takes repetition of column spacings into account. The system permits some columns to be omitted from the column grid and allows also application of columns outside the regular grid. In specifying the *floor system* only the load-bearing direction of each floor field has to be specified; slabs and beams are automatically distributed by the computer. Identification and numbering of each structural element are also automated.

To *check* the input data, the program system presents several facilities:
— the line printer reprints the total input data set;
— the plotter produces preliminary floor plans showing the arrangement of all structural members so as the computer developed the structural system based on the input data, indicating the automatic numbering of the members;
— the reading and processing programs carry out numerous checks on the data set: in case of errors or contradictions they give error messages.

6. The output system

The output results supplied by the program system appear partly on the line printer, partly as drawings provided by the plotter. In filling out the data sheets, the designer may make a choice among options, defining which kinds of output results — enumerated below — he wants to be printed out or to be traced.

6.1 Line printer output

Outputs on the line printer are:
— input data reprinting;
— design values of internal forces of the system components and combination of internal forces for each storey and member;
— results of member selection and schedules. Member selection means that the program checks the load-bearing capacity of the structural members, with the dimensions specified by the designer (using the load-bearing capacity data stored in the data base). If the catalogue of the "BVM-TIP" system provides the possibility, among members of identical geometry the computer choses the most economical reinforcement variant granting the member a safe load-bearing capacity, and prints out the system catalogue code of the member complying with the given geometry and strength requirements. The output indicates if there is no member meeting the given geometry and strength conditions in the data base of

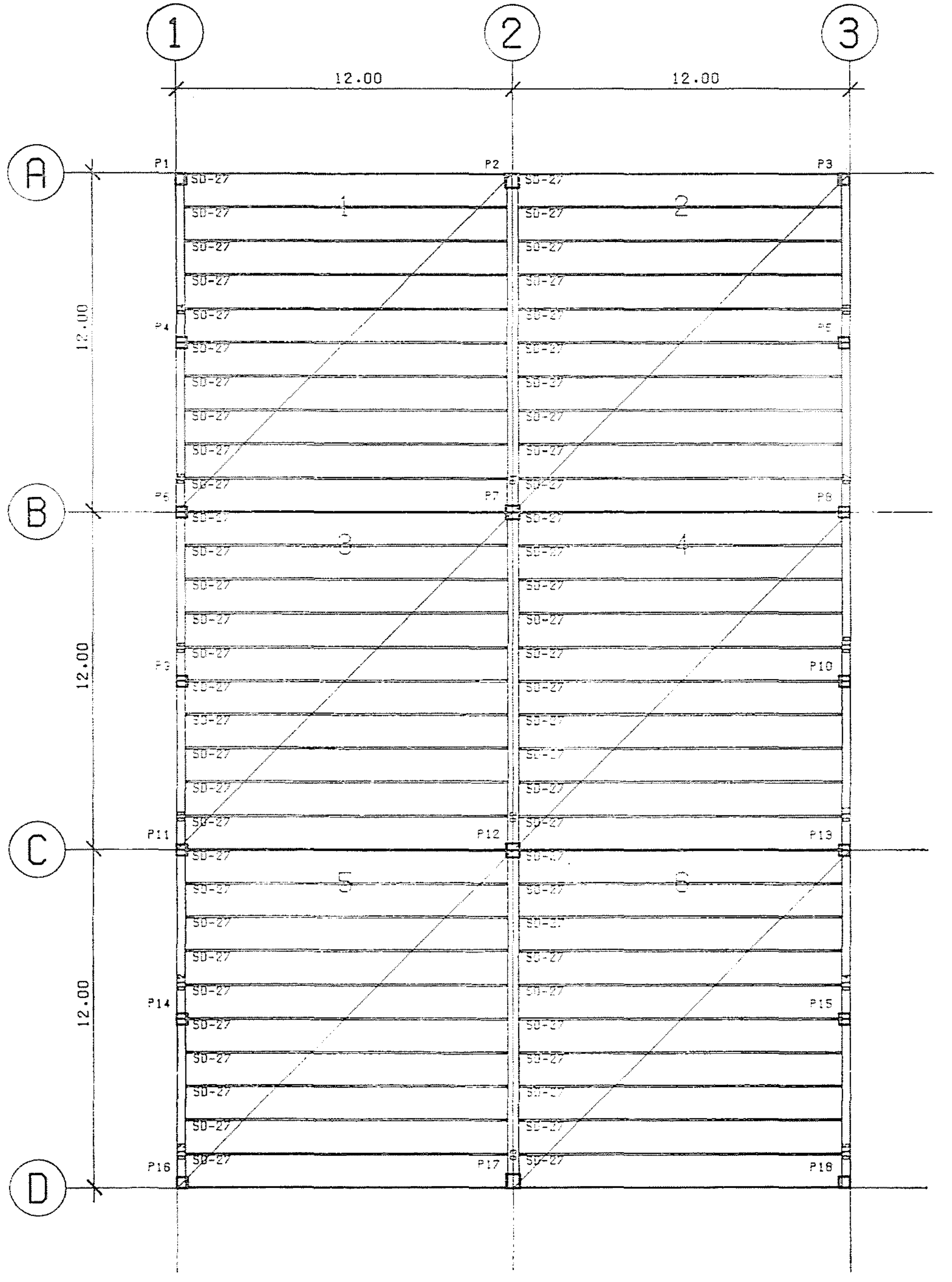

Fig. 3. Preliminary floor plan of a single-storey building

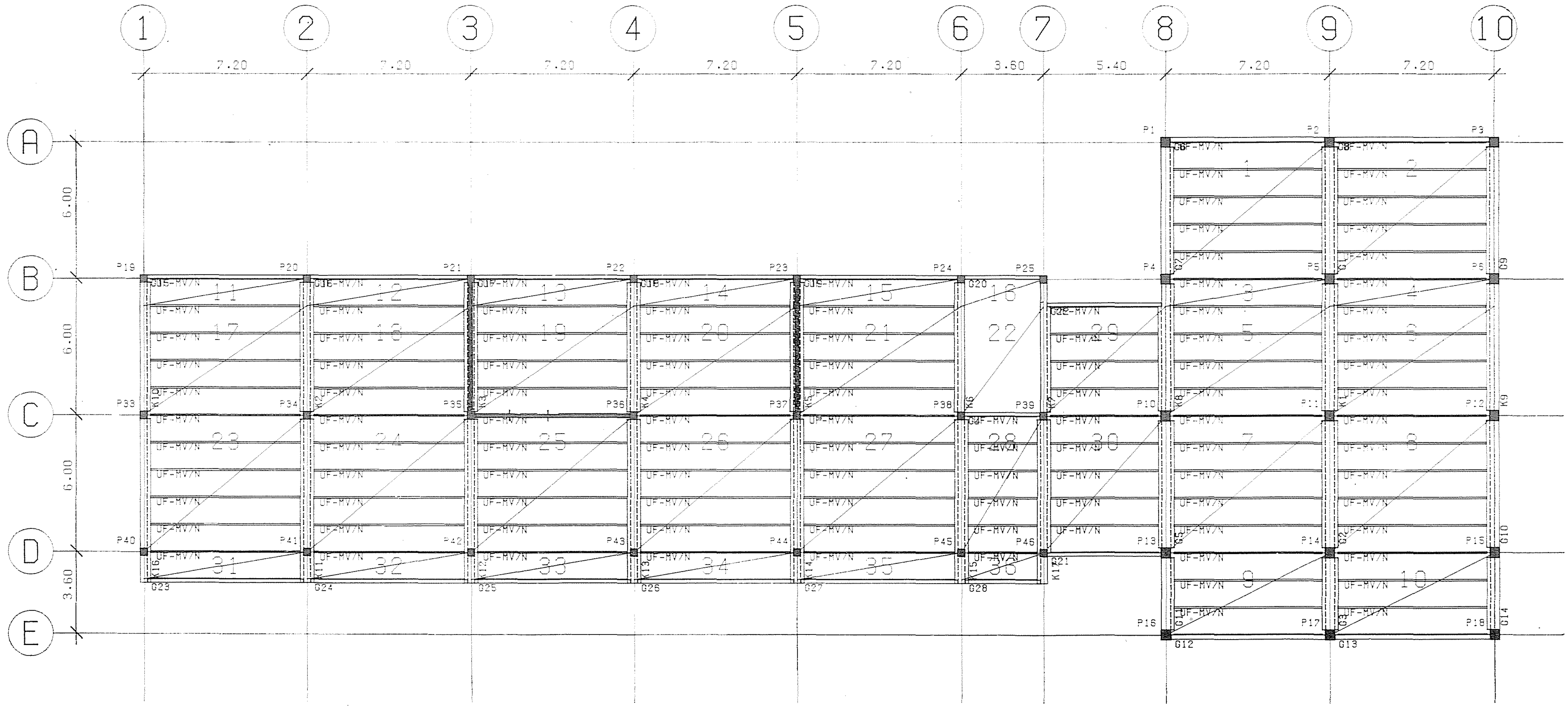

Fig. 4. Preliminary floor plan of a multi-storey building

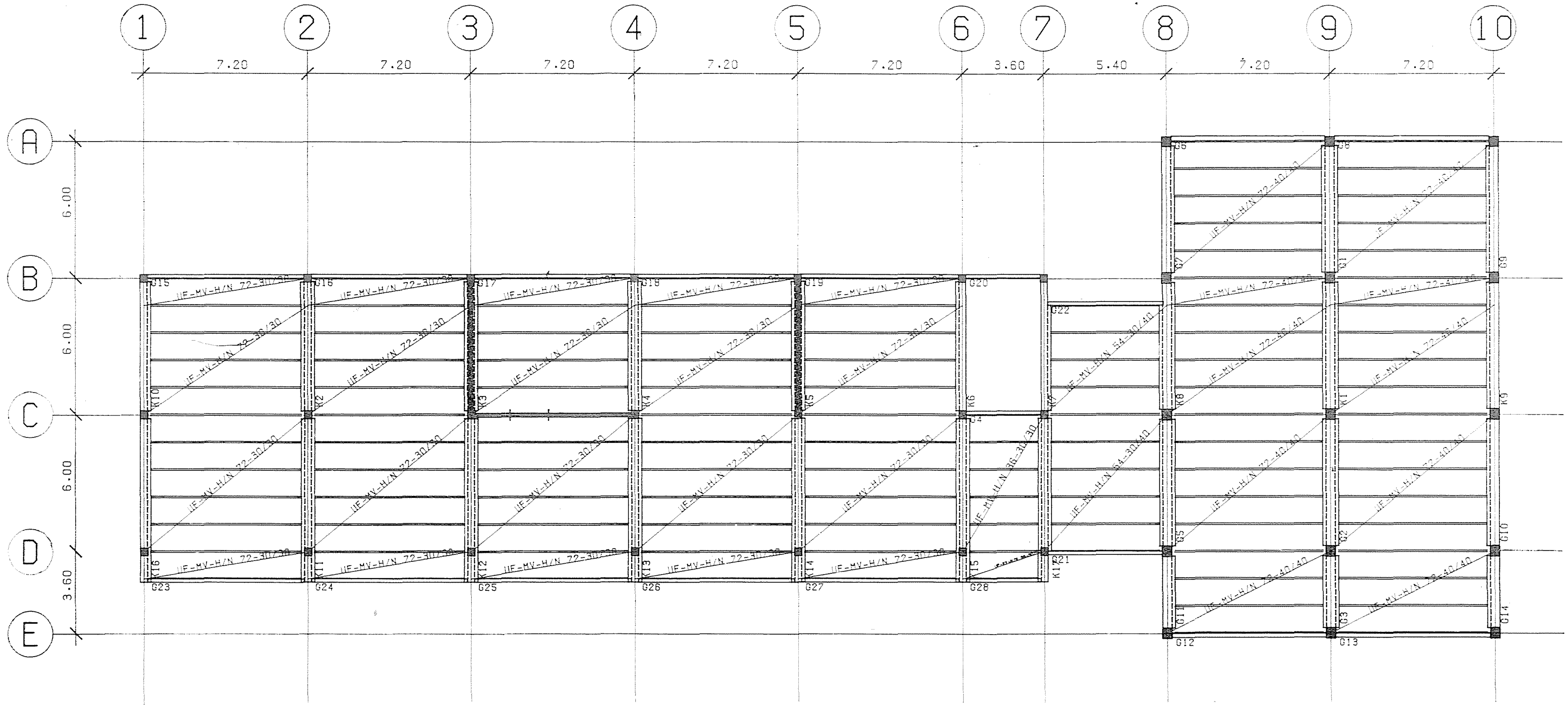

Fig. 5. Floor slab plan of a multi-storey building

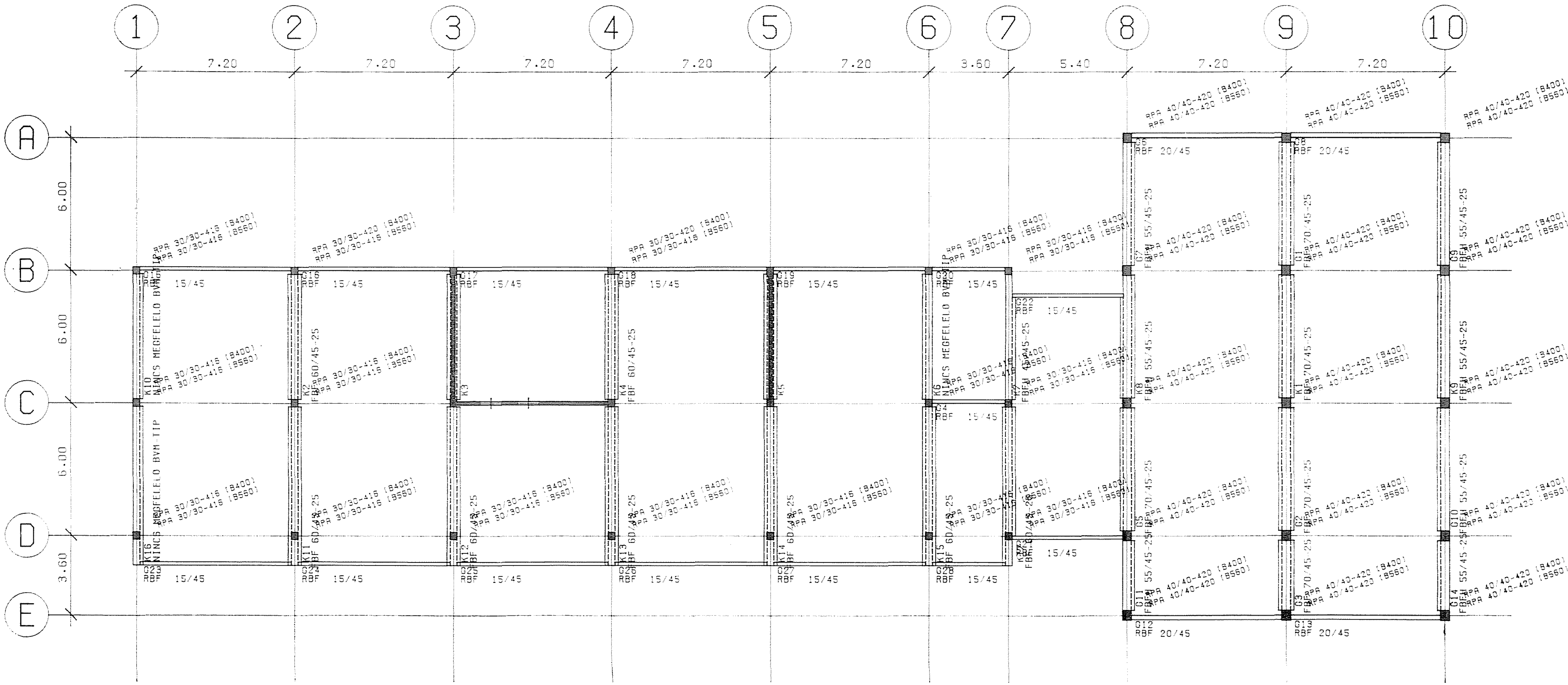

Fig. 6. Column/beam plan of a multi-storey building

the system, and possibly tries again the design with another member, with larger dimensions. Member selection is carried out member-type-wise (floor slab, beam, column) and storey by storey. Also schedule is made member-type-wise, at first storey by storey, then summing up each member type for the entire building.

6.2 Plotter-traced plans

Beside the mentioned preliminary floor plans traced by the plotter, the program system produces also phase floor plans, separately for the columns and beams, and separately for the floor slabs. The phase floor plans contain layout of the structural members, their codes according to the catalogue and the member schedule for the given storey.

Remind that the graphical output is carried out parallel to the calculations, based on input data and on calculation outputs; thus no separate data specification is needed for the drawings. Preliminary floor plans of a single-storey and a multi-storey building are seen in Figs 3 and 4, respectively, layout of floor slabs of a multi-storey building is seen in Fig. 5. Figure 6 shows layout of columns and beams for the same building.

7. Some characteristics of the algorithm

7.1 Structural model

Structural models of the single-storey or multi-storey system variants were established according to principles in the catalogue of the building system, described under 2.

7.2 Loads

The structural members are exposed to both vertical and lateral loads and effects. *Vertical* loads are due to uniformly distributed loads and to individual floor loads, loads of the façade wall units, and occasionally (for the single-storey variant) to crane loads. The computer automatically calculates and takes into account the dead load of beams, girders and columns.

Among lateral loads and effects the program system takes the following into consideration:

— wind load;
— braking and lateral forces of the crane;
— uneven distribution of vertical loads;
— assembly inaccuracies of the columns;
— effect of temperature changes;
— shrinkage of precast floor units.

Lateral loads and effects, in compliance with the appropriate standard specifications, are calculated automatically by the program system.

It has to be mentioned that wind loads are more precisely calculated than in the usual manual methods because the possible oblique wind directions are also considered; it has been proved that — according to the standard in virtue — critical wind loads are exactly those due to winds including an oblique angle with the longitudinal axis of the building.

7.3 Analysis of structures

The program system reckons with the most unfavourable arrangement of loads and internal forces, and the load factors admitted by the standard, and bases the analysis on them. Analysis is carried out to prepare both the limit state design and serviceability limit state design of members. For *floor slabs* the total loads are significant; the program processes of them the design values of shear forces and bending moments, as well as from the basic values of the loads the serviceability limit state moment necessary for testing the crack width.

For *floor beams*, in every cross section critical for the position of the prestressing tendons, the program determines:

- maximum values of the positive and negative bending moments with the respective shear force and torsional moment;
- maximum values of the positive and negative shear forces with the respective bending and torsional moment;
- maximum values of the positive and negative torsional moment with the respective bending moment and shear force.

For *columns*, vertical loads may result in six combinations of critical internal forces for each storey:

1. N_{max} with the respective M_x and M_y
2. $+M_{xmax}$ with the respective M_y and N
3. $-M_{xmax}$ with the respective M_y and N
4. $+M_{ymax}$ with the respective M_x and N
5. $-M_{ymax}$ with the respective M_x and N
6. N_{min} with the respective M_x and N_y.

For columns of *single-storey buildings*, beside the internal forces above, also lateral forces and effects have to be taken into account.

The program has been prepared to process, after thorough tests, the internal forces from the eight arrangements of loads, according to the following table:

Simultaneous internal forces	Emphasized	Dead load	From traveling cranes		Snow	Wind	Temperature, shrinkage
			building	column			
1. Nmax, M	snow	max	$\alpha \cdot$ max	$\alpha \cdot$ max	max	$\alpha \cdot$ max	$\alpha \cdot$ max
2. Nmax, M	crane	max	max	max	$\alpha \cdot$ max	$\alpha \cdot$ max	$\alpha \cdot$ max
3. N, Mmax	crane	max	max	int	$\alpha \cdot$ max	$\alpha \cdot$ max	$\alpha \cdot$ max
4. N, Mmax	wind	max	$\alpha \cdot$ max	$\alpha \cdot$ int	$\alpha \cdot$ max	max	$\alpha \cdot$ max
5. N, Mmax	temp.	max	max	int	$\alpha \cdot$ max	$\alpha \cdot$ max	max
6. Nmin, M	crane	min	max			$\alpha \cdot$ max	$\alpha \cdot$ max
7. Nmin, M	wind	min	$\alpha \cdot$ max			max	$\alpha \cdot$ max
8. Nmin, M	temp.	min	$\alpha \cdot$ max			$\alpha \cdot$ max	max

In the table α is the simultaneity factor and "int" the intermediate value of the crane load where the column is unilaterally loaded by a traveling crane.

If there is no crane in the building, combinations 2, 3, and 6 are omitted.

Lateral loads and effects may act in different bending planes. Thus the eight dangerous directions of the wind loads involve eight bending planes; the positive and negative deformations of the floor slab (due to temperature variations and shrinkage) give two more bending planes for each column independent of the previous ones. The crane braking force, the lateral force and the torsional moment acting on the floor slab indicate six dangerous directions — whereas the braking force and the lateral force acting on each column signify further six ones. Among the above described cases the program determines for each column, in all the eight combinations of forces, an axial load and two-way values M_x and M_y belonging to the 22 bending planes simultaneously

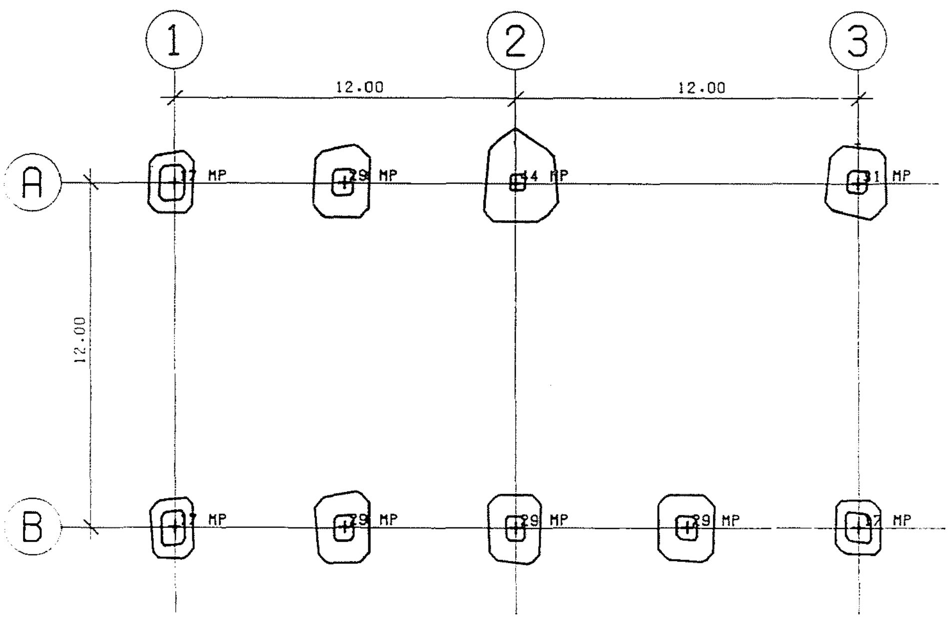

Fig. 7. Ranges of loading of the columns of a single-storey building

possible (for each column at most 8 axial loads and 352 bending moment components). These constitute the ranges of loading of the columns. Ranges of loading of a single-storey building traced by the plotter are shown in Fig. 7.

The program distributes the lateral forces between columns in proportion to their secondary stiffnesses.

For columns of *multi-storey buildings* the maximum and minimum values of the axial load, transmitted from the upper storeys, have to be superimposed to the 6 combinations of internal forces at each storey. For these columns altogether 30 arrangements of loads must be considered.

The increment of eccentricity specified in the standard is taken automatically into account by the program system for both sorts of columns.

The lateral forces acting on the totality of *shear walls* are calculated by considering eight different wind load directions and for each one two kinds of unfavourable column inclination; also vertical loads on each wall are calculated. The lateral forces are distributed between walls, and the internal forces determined by a program developed in a design office and joining the program system of our Department.

7.4 Member selection and design

A structural design program system becomes a real help in design, when — beyond the *analysis* (i.e. determination of internal forces) — it also performs the design of structural components. In an industrialized system, in case of buildings to be erected of precast members, dimensioning is replaced by selecting the proper members from a catalogue. This could be done by checking every system component meeting the given geometrical conditions in ultimate and serviceability limit states and choosing the economically most suitable member. However — to save computer time — it seemed more practical to store limit values of load bearing, crack width and deformation in the *data base* set up previously on the magnetic disc of the computer, and to accomplish the selection based on these limit values.

In the case of r.c. structures the building up of the data base requires special considerations, because the limit values are interdependent.

In case of beams the bending moment—torsional moment and the shear force—torsional moment, in case of columns the axial load and the two kinds of bending moments have to be considered together. Therefore the above limit values cannot be stored separately, but only coupled in form of so-called ranges of *load-bearing capacity*; checking is carried out by comparing the ranges of loading and load-bearing capacity.

Figure 8 shows diagrams for relationships of load-bearing data for a prestressed beam. In Fig. 9 the ranges of load-bearing capacity of a r.c. column have been plotted, i.e. the limit values of the two-way bending moments belong-

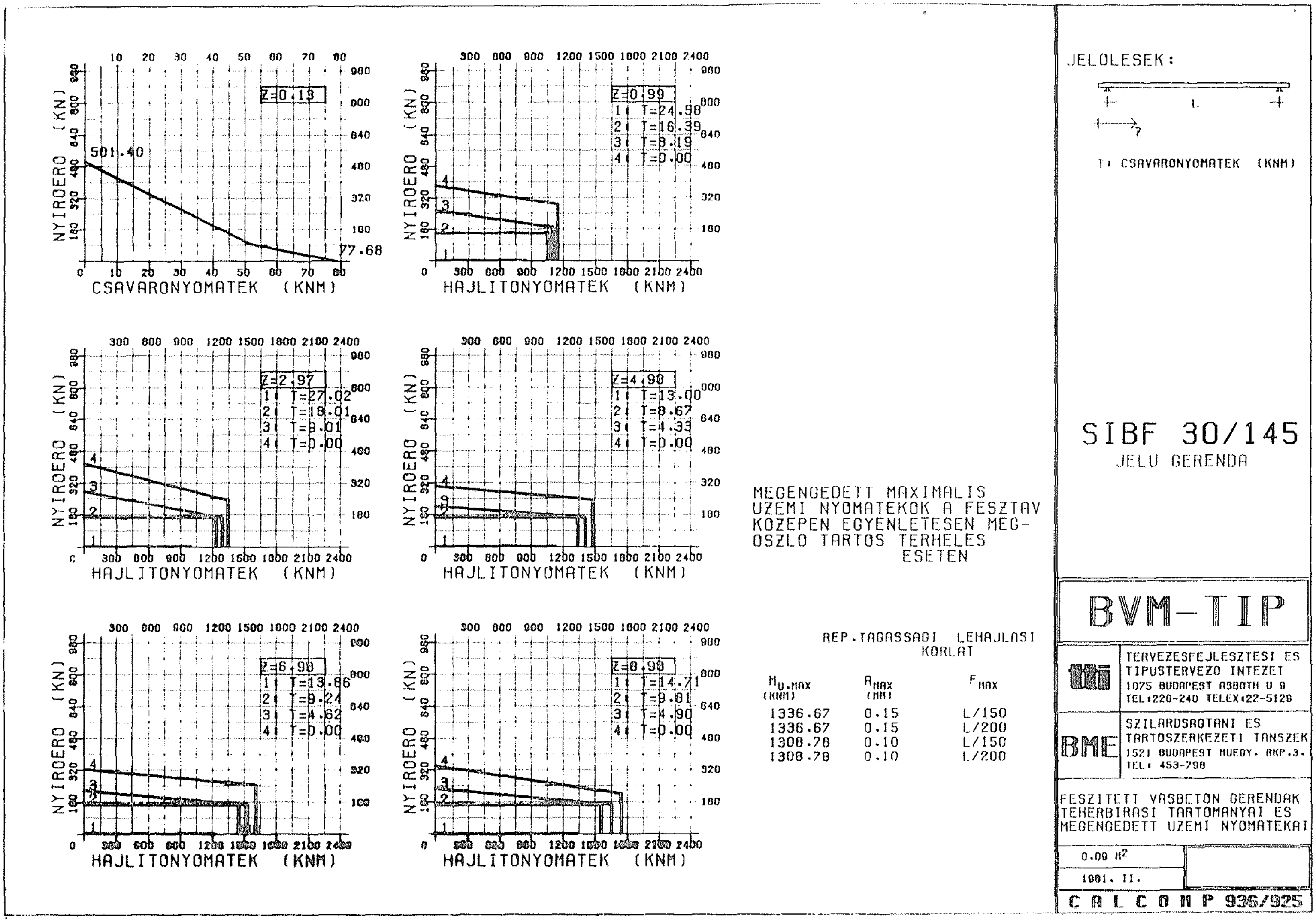

Fig. 8. Load-bearing diagrams of a prestressed r.c. beam

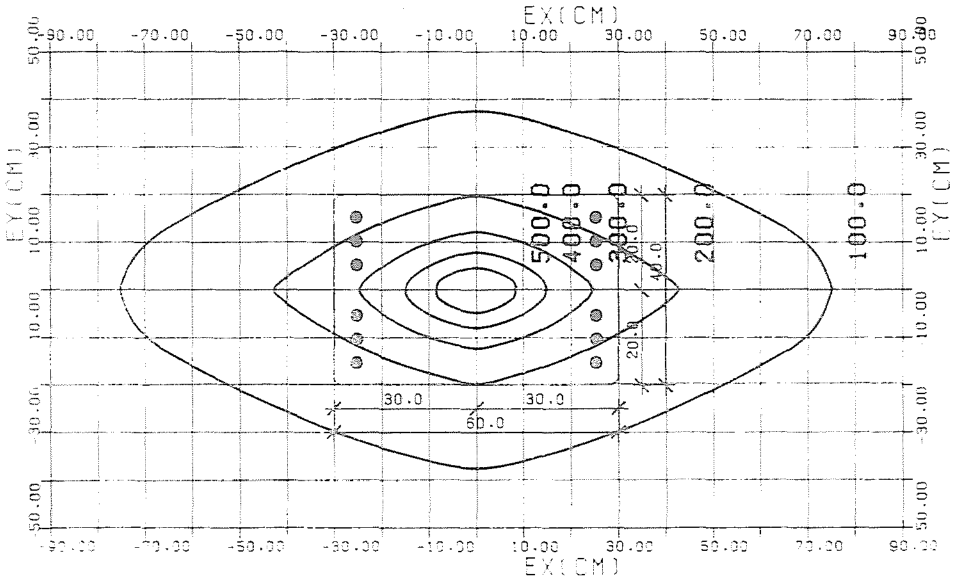

Fig. 9. Ranges of load-bearing capacity of a r.c. column

ing to the given axial loads. Both diagrams have been traced by a plotter, based on separate programs. Similar figures for all units in the building system have been compiled in a manual for designers who for some reason cannot make use of the complete program system.

8. Structure and use of the program system

The program system has been developed for the Hungarian-made mini-computer R-10 of the Institute for Design Development and System Design. The core store capacity of the computer is 64 kbytes; two magnetic disc background stores of 2, 5 Mbytes and two magnetic tape units are attached to it. The computer is off-line connected with a plotter type CALCOMP 936/925.

Structure of the program system was determined by the characteristics of the computer with a relatively small storage capacity. The system consists of 11 main programs, running one after the other; only one main program being at a time in the operative memory. This system is a facility to store the job control statements on magnetic disc and to activate the program system by means of a single job control card.

The programs, the store of load-bearing data of the precast members, as well as the input and the intermediate data library of the building under design are stored in magnetic disc files. Magnetic tapes are used only for recording data of the graphic material. Schematic flowchart and data flow set-up are shown in Fig. 10.

Since September 1981 the Institute for Design Development and System Design has been using continuously the program system. Up to now about 30, mostly really constructed buildings have been processed.

The Department and the above-mentioned Institute cooperate in transmitting the program system to the new Hungarian computer R-11 having a higher capacity and a time sharing system. This computer has a core store capacity of 718 kbytes with four 50 Mbytes magnetic disc backing stores.

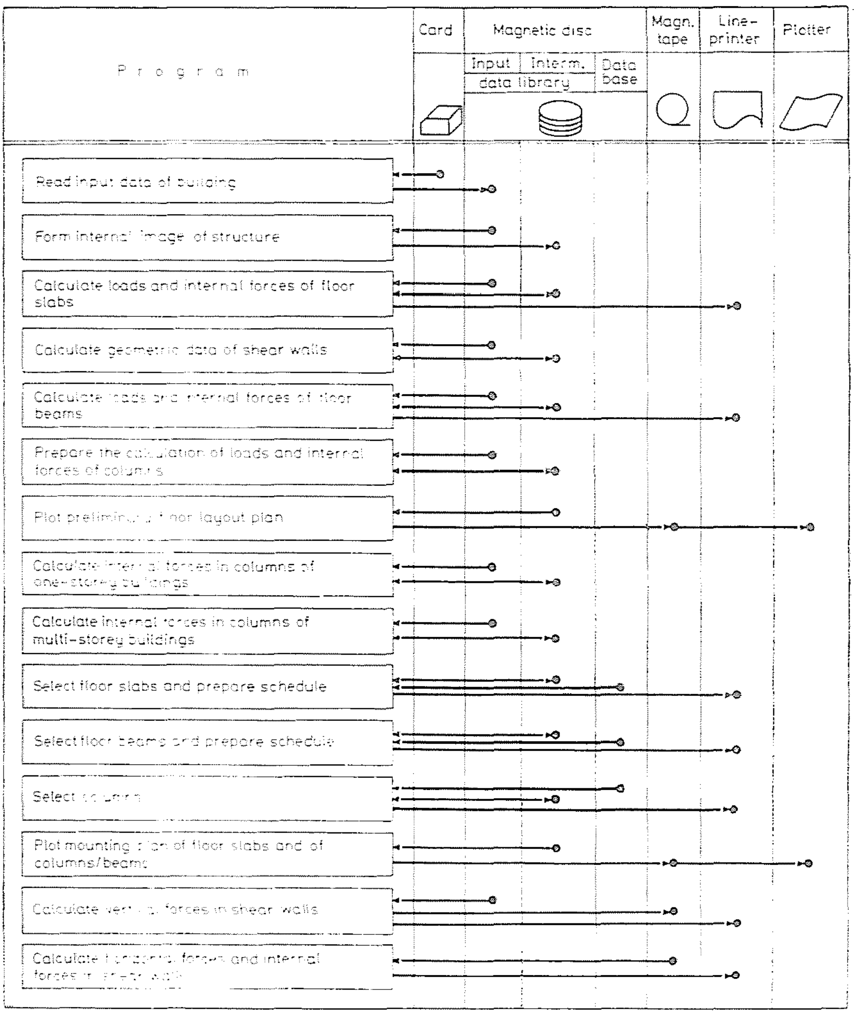

Fig. 10. Schematic flowchart and data flow of the program system

The higher capacity permits to increase the volumes of the computed structures. On the computer R-11 the program system will also be run interactively treated from terminals, against the batch system used till now.

Summary

Rapid development of computer technology made it possible to replace some computer calculations in engineering design work by comprehensive computer-aided design or automated design systems illustrated here on a realized example. Based on the know-how of the Swedish firm AB STRÄNGBETONG, the Concrete and Reinforced Concrete Works and the Institute for Design Development and System Design developed the BVM-TIP r.c. framework building system. A team of the Department of Strength of Materials and Structures of the Technical University, Budapest, developed a sub-system for the computer-aided structural design. The computer system requires relatively few input data to do the complete structural analysis and design of single- or multi-storey buildings in the BVM-TIP system of any kind of ground plan. It choses from the data base the system components coping with geometry conditions and safety conditions in ultimate and serviceability limit states. It traces floor plans on plotter and prepares the schedule of the structural members.

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