PERIODICA POLYTECHNICA SER. CIVIL ENG. VOL. 36, NO. 3, PP. 271–282 (1992)

LOAD-BEARING CAPACITY OF IMS FLOORS AFFECTED BY CABLE CORROSION

GY. FARKAS,* J. GYÖRGYI,** A. LOVAS** and E. MISTÉTH,*

Faculty of Civil Engineering
*Department of Reinforced Concrete Structures
**Department of Mechanics
Technical University, H–1521 Budapest

Received: June 22, 1992

Abstract

IMS structures are skeletons assembled of precast concrete units, where floor units are connected to columns by post-tensioning. Ulterior tests show cables to exhibit significant corrosion in critical floor cross-sections.

Variation of the failure risk of similar floor structures has been examined taking cable corrosion into consideration. Expected values of critical internal forces and load-bearing capacities of critical cross-sections have been determined by probabilistic methods. Internal forces computation applied 2D and 3D lattice programs run on IBM 386 computer.

According to test results on a typical floor constructed 15 years ago assuming corrosion as probabilized from disclosures, failure probabilities of critical cross-sections compared to the original condition much increased, exceeding by about two orders the Hungarian Standard requirement.

According to investigations, if in a cross-section, cables of a given direction undergo total corrosion or rupture, internal forces are rearranged, leading to progressive collapse of the floor.

Keywords: post-tensioning floor, cable corrosion, probabilistic design, risk of failure.

Introduction

An IMS structure is a skeleton assembled of precast reinforced concrete units, with the peculiarity that in fields between columns one or more large ribbed floor units are axially connected to the columns by post-tensioning (*Fig. 1*). Load transfer between column and floor is by friction arising from prestressing.

In a floor field several — two or four — floor units are accommodated, then mostly also intermediate post-tensioning is applied. In addition to providing for vertical load transfer, tensioning contributes also to the moment bearing, of the floor. To increase moment bearing cables are generally conducted not in the strength axis of the floor, and cables are generally tensioning vertically, too (*Fig. 2*). The vertical tensioning of a cable causes a concentrated force system opposite to the load acting on the structure, reducing thereby its internal forces.

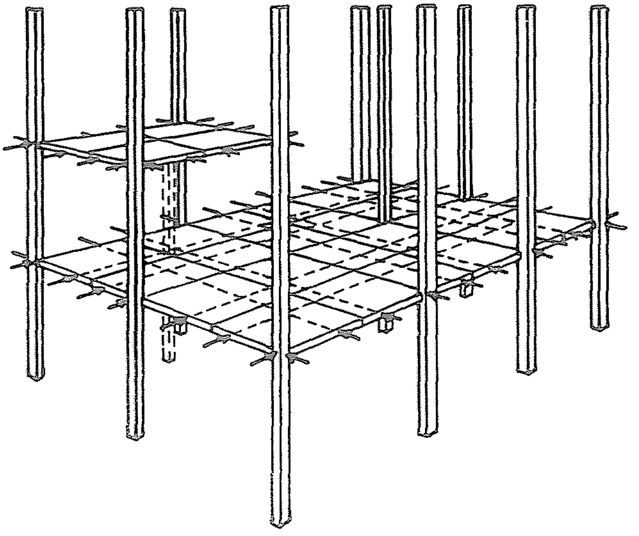

Fig. 1. IMS structural system

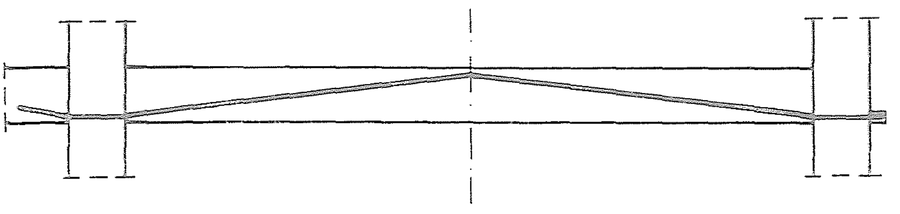

Fig. 2. Vertical tensioning of a cable

Disclosures on not too old IMS buildings in the past two years showed in structures significant corrosions, even ruptures of cables essentially impairing load-bearing capacity of the floor. In Hungary, some 370 000 m^2 of floors have been built with IMS system, thus, prediction of the loss of safety of load-bearing capacities of such floors is of importance.

Tempotal course of the failure probability due to corrosion in typical cross-sections of the floor have been investigated by methods of mathematical statistics.

Ultimate Moment of Characteristic Cross-Sections

Failure safety of floors is essentially determined by their moment bearing capacity. Expected values of the ultimate moment of characteristic cross-sections have been computed.

Fundamental Assumptions

Both concrete and strands of a floor slab are more or less fragile materials, of that the strength and its probabilistic characteristics are the most reliably described by the Weibull distribution. Its distribution function is:

$$\begin{aligned} F_1(x) &= 1 - \exp\{-[\lambda_1(x - x_{01})]^{r_1}\} && \text{if} \quad x > x_{01}, \\ F_1(x) &= 0 && \text{if} \quad x < x_{01}, \end{aligned} \tag{1}$$

and its density function:

$$\begin{aligned} f_1(x) &= r_1\lambda_1(x - x_{01})^{r_1-1} \exp\{-[\lambda_1(x - x_{01})]^{r_1}\} && \text{if} \quad x > x_{01}, \\ f_1(x) &= 0 && \text{if} \quad x < x_{01}. \end{aligned} \tag{2}$$

The most reliable parameters x_{01}, λ_1 and r_1 of the distribution function may be determined, after MISTÉTH (1991), by the maximum likelihood method by trial and error.

According to test results of BÖLCSKEI and MISTÉTH (1971) breaking force of the strands decreases if their length increases. In the case of distribution function (1), expected value of tensile strength of a strand of the length L is obtained from

$$\sigma_L = \sigma_{0.5} \left[x_{01} + \frac{M}{r_1\lambda_1 \left(\frac{L}{0.5}\right)^{\frac{1}{r_1}}} \right], \tag{3}$$

where $\sigma_{0.5}$ is expected value of strength of a wire of 0.5 m length. Standard deviation of wire strength vs. length decreases as:

$$s_L^2 = s_{0.5}^2 \left(\frac{0.5}{L}\right)^{\frac{2}{r_1}}, \tag{4}$$

The normal steel bars B 60.40 in precast slabs of IMS floor structures have plastic properties. Strength of such materials is the closest described, after

KORDA (1972), by the Pearson III. distribution. Parameters of the density function of distribution can be determined, after MISTÉTH (1991), also by the maximum likelihood method.

According to MISTÉTH (1987) the strength of floor materials decreases with time at a rate:

$$\sigma(t) = 1 - \frac{1}{3}\left(\frac{t}{t_0}\right) - \frac{1}{3}\left(\frac{t}{t_0}\right)^2 - \frac{1}{3}\left(\frac{t}{t_0}\right)^3 , \tag{5}$$

while strength variance increases with time, at a rate:

$$s(t) = 1 + 4\left(\frac{t}{t_0}\right) , \tag{6}$$

where the t_0 value may be assumed to be 500 years.

To determine the reduction of cross-section of strands due to corrosion, it is assumed that cross-sectional area is zeroed after t_1 years. Increase of the standard deviation of the loss of cross-section due to corrosion is assumed to be similar to that of strength.

Expected Value of the Ultimate Moment

A typical cross-section of the floor structure and the principle of determining the Mörsch ultimate moment of the cross-section are seen in *Fig. 3.*

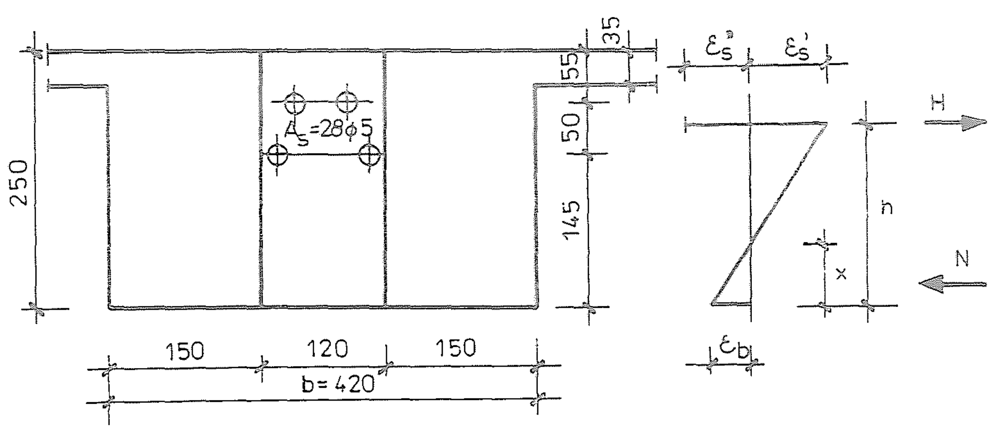

Fig. 3. Principle of determining the ultimate moment

Assuming the cross-section to remain plane in ultimate condition, the Mörsch ultimate moment becomes:

$$M_R = \sigma_b b \left(B + \sqrt{B^2 + \frac{C}{h}} - \frac{B + \sqrt{B^2 + C}}{2} \right) , \tag{7}$$

where

$$B = \frac{A_s}{2\sigma_b \cdot b} \left[\sigma_{sF} + E_s(\varepsilon_s'' - \varepsilon_b) \right] \tag{8}$$

and

$$C = \frac{A_s}{\sigma_b \cdot b} E_s \varepsilon_b h , \tag{9}$$

where σ_b is ultimate stress of concrete, ε_s'' is effective tensile strain of steel, σ_b is ultimate strain of concrete, and σ_{sF} is yield stress of the cable, E_s is Young modulus of steel.

Substituting expected values of the eight parameters into *Eq.* (7) yields a fair approximation of the expected value of the ultimate moment. Standard deviation and slope of the ultimate moment can be calculated in knowledge of standard deviations and slopes of the variables.

Determination of Internal Forces of the Floor

Expected stresses in critical cross-sections have been determined under critical load of the floor, taking probability characteristics of loads by means of a computer program.

Loads

Random distribution of dead loads has been assumed to be lognormal with a density function:

$$\begin{aligned} f(g) &= \frac{1}{\sqrt{2\pi}\sigma(g - g_0)} \exp\left\{ -\frac{[\ln(g - g_0) - u_0]^2}{2\sigma^2} \right\} \qquad \text{if} \quad x > x_{01} , \\ f(g) &= 0 \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \text{if} \quad x < x_{01} . \end{aligned} \tag{10}$$

Expected value of density function (10) results from

$$\overline{g} = g_0 + \exp\left(u_0 + \frac{\sigma^2}{2} \right) \tag{11}$$

permitting to compute all probability characteristics, taking minimum value $g_0 = 0.7\,\mathrm{g}$ and 0.06 relative standard deviation valid for building materials.

Live loads of buildings are distributed loads with rather short-time validity of basic values. Distribution function of yearly maxima of the live load follows the upper first extremal distribution, such as:

$$F_3(p,t) = \exp\left\{-\exp\left[-\lambda_3(p-p_0) - \frac{\ln t}{\lambda_3}\right]\right\}. \tag{11}$$

According to the Hungarian Standard basic value of the live load of such buildings is $1.5\,\mathrm{kN/m^2}$ while according to statistical data collection, yearly maxima have an expected value of $\approx 0.52\,\mathrm{kN/m^2}$ and a standard deviation of $0.322\,\mathrm{kN/m^2}$ values permitting to compute fundamental values of live loads at the given age of floor. These have been reckoned with in determining internal forces.

Computation of Internal Forces

Computation using a 2D lattice model

When applying an in-plane lattice model, bending and twisting moment, as well as shear forces are computed from loads normal to its plane. With this model, there is no means to reckon with normal forces in the ribs and compressive forces arising at the columns. A usual assumption is to take the normal force along the line identical to the horizontal component of outer stressing acting in the given line.

The model can be applied if a compressive force high enough to provide for rigid connection between columns and joining floor unit ribs arises. This is the case where cables are but slightly corroded. The model is also valid, with a slight inaccuracy, when strands between ribs and columns are perfectly corroded, permitting them to be detached.

Computation using a 3D lattice model

Analysis using a spatial lattice model results, in addition to those above, in plane bending moments, shear forces arising in the ribs, and also normal forces.

It offers a means to check floor unit to floor unit, floor unit to column connections (at this latter, important shear forces arise).

Performing analyses for rigid connections shows normal forces not to be constant along the given line. Along the columns and at the ribs in the fields, normal forces are rearranged as a function of the proportion of stretches and of rib cross-sections.

The applied model permits to use — in case of cable corrosion — part of the stretching force, and for rupture, all the stretching forces on the beam as force distributed along the anchorage length (indicating vertical and horizontal components, and reckoning with specific moments from eccentricity). Assuming cable rupture at certain spots, numerical tests have demonstrated that at rupture spots tension arises in connections assumed to be rigid, so detachments have to be reckoned with.

Thereby, in the case of rupture, computations have to refer to a structure consisting of bars connected according to those above.

Analysis may also point out that although at some nodes a compressive force arises, but the friction obtained for the given friction coefficient is less than the shear force at that node. All these involve that at the given node a displacement may occur so that kinematic loads computed from it reduce the shear force to opportune level. The required displacement on the original structure may be obtained from analysis of a statically determinate primary structure.

Computation Results

The Floor

According to fundamentals above, a load safety of a typical two-unit IMS floor, 6 by 6 m divisions, two-way symmetrical and in one direction cantilever has been examined. Floor plan of one quarter of the floor and its mesh divisions for computing the internal forces are seen in *Fig. 4*.

Stars and circles in the figure show vertical tensioning spots. Along the principal stresses, four compound cables of 7×0.5 mm wire groups, while along the by-stresses, one compound cable 7×0.5 mm have been assumed.

Strength characteristics of the stressing cables have been determined from a sample of 1000 stressing wires (mark 1670.50) tested by the Institute of Building Qualification in 1977. Experimentally demonstrated $\sigma - \varepsilon$ diagrams of the wires have been plotted in *Fig. 5*.

Based on disclosements in IMS buildings it was assumed that total corrosion of stretching cables in critical cross-sections near the columns may occur in $t_1 = 50$ years.

Floor slabs are made of concrete with a strength mark C 30, having properties of a sample of 516 specimens tested by the Institute of Building Qualification in 1982. Concrete corrosion was not taken into account.

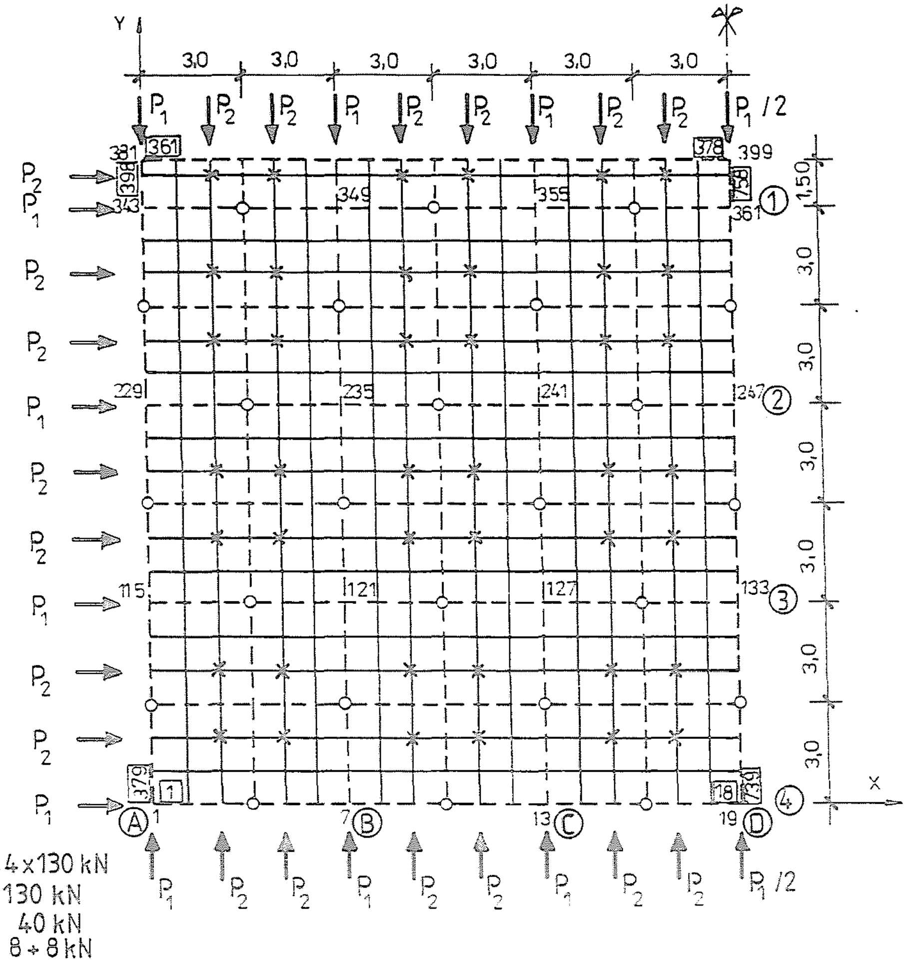

Fig. 4. Mesh division of the floor

Expected values of ultimate moments of critical cross-sections have been computed according to item 2.2.

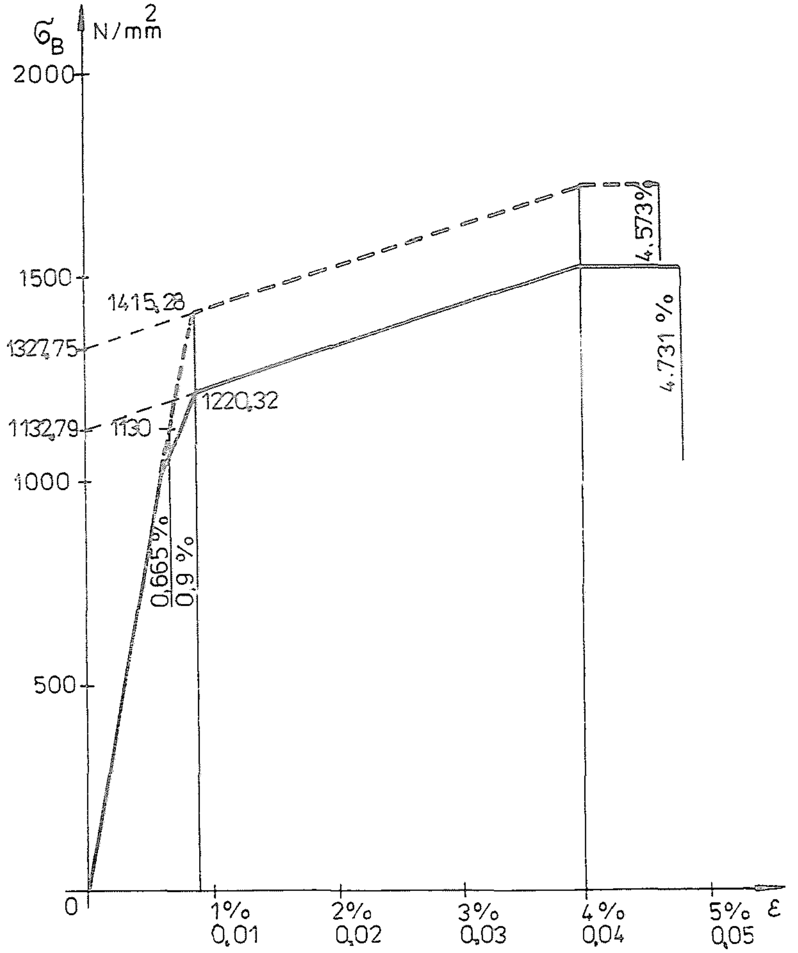

Fig. 5. $\sigma - \varepsilon$ diagrams of the wires

Failure Probabilities of Critical Cross-Sections

Maximum moments arising in one quarter of a floor field 6 by 6 m computed by means of a 2D lattice model is seen in *Fig. 6*.

Assuming corrosion-proof cables in critical cross-sections above supports, a failure probability $p_{R_s} = 2.418 \cdot 10^{-6}$ was obtained, less than the standard requirement of $p_{\text{opt}} = 10^{-4}$, hence the structure is satisfactory.

Again, taking 30 % corrosion of wires, likely to occur in 15 years after construction, into consideration, in conformity with the disclosures,

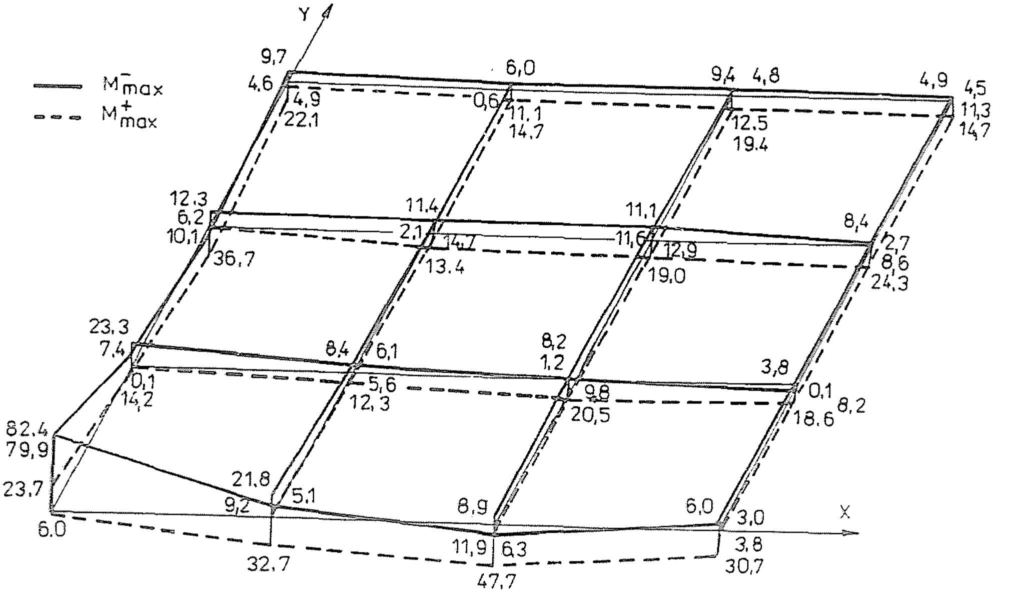

Fig. 6. Maximum moments in one quarter of a floor field

failure has a probability $p_{R_s} = 4.23 \cdot 10^{-2}$ significantly beyond the standard requirements. Thereafter, the failure probability abruptly increases.

Risk of Progressive Collapse

In disclosures it was often observed that in a cross-section near the support, much of the cables were disrupted. Therefore redistribution of internal forces has been analyzed also for the case where in a critical cross-section, cables in a given direction got disrupted. Now, expected critical bending moment values have been determined on a 3D lattice model. Moment redistribution for the rupture of single cables is seen in *Fig. 7*.

Analyses have shown that if at a node cables in one direction got disrupted, probability of failure due to a moment of the same node in the other direction significantly increases, likely to result in progressive collapse of the floor structure.

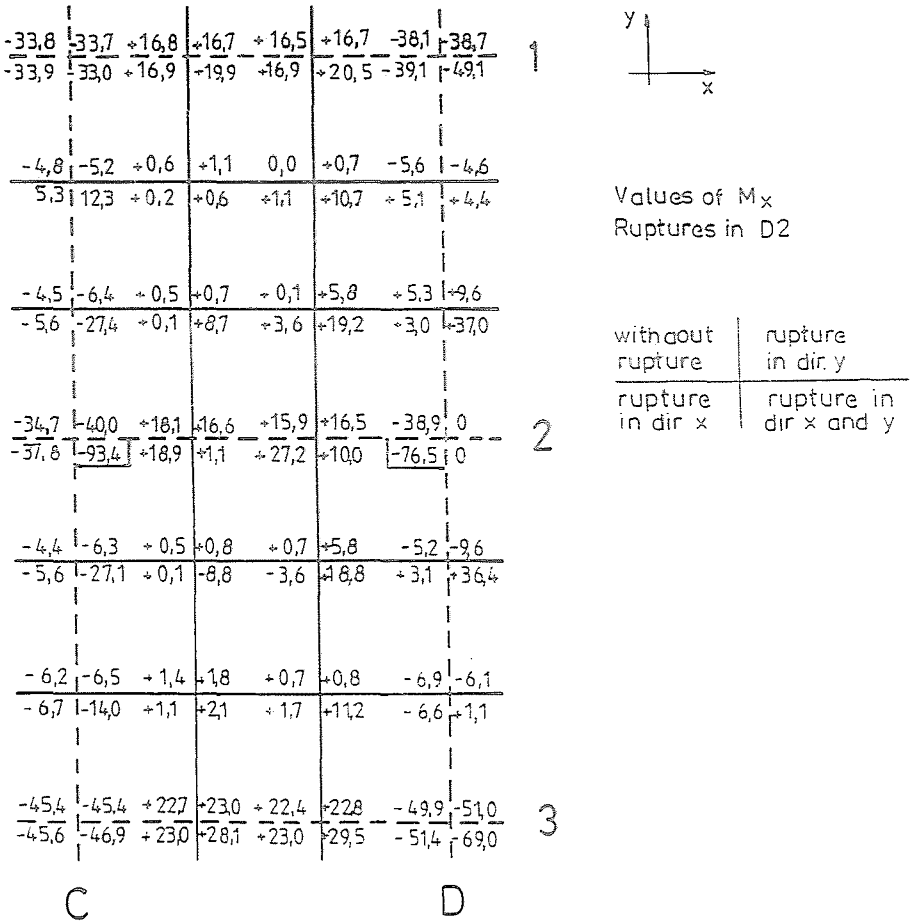

Fig. 7. Moment redistribution for the rupture of single cables

Conclusions

Failure probability of a floor structure assembled by post-tensioning from precast concrete floor units has been examined, taking cable corrosion into consideration. Expected values of critical cross-sections and load-bearing capacity of the structure have been determined on probabilistic considerations. Numerical analysis of the internal forces relied on 2D and 3D lattice programs.

According to computations, in the case of rupture of cables in one direction in a cross-section from any cause, redistribution of internal forces may lead to the progressive failure of the floor.

References

BÖLCSKEI, E. – MISTÉTH, E. (1971): Strength Characteristics of Prestressing Cables, *Mélyépitéstudományi Szemle*, 1971/4. pp. 145–154. (in Hungarian).

KORDA, J. (1972): Tension-Compression Strength Qualification of Elasto-Plastic Materials Using Probabilistic Theory, *Mélyépitéstudományi Szemle*, 1972/4 pp. 175–188. (in Hungarian).

MISTÉTH, E. (1987): In Time Changing of Load-Bearing Capacity, *Mélyépitéstudományi Szemle*, 1987/1. pp. 15–23. (in Hungarian).

MISTÉTH, E. (1991): Probabilistic Mechanical Analysis of IMS Floor Slabs, Study, Department of Reinforced Concrete Structures, TUB, 1991. (in Hungarian).

Addresses:

Dr. György FARKAS
Department of Reinforced Concrete Structures
Technical University,
H–1521 Budapest, Hungary

Dr. Antal LOVAS
Department of Mechanics
Technical University,
H–1521 Budapest, Hungary

Dr. József GYÖRGYI
Department of Mechanics
Technical University,
H–1521 Budapest, Hungary

Professor h.c. Endre MISTÉTH Doctor of Techn. Sci.
Department of Reinforced Concrete Structures
Technical University,
H–1521 Budapest, Hungary