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COMPARATIVE MODELS OF PRECAST WAFFLE SLABS DUE TO POST-TENSIONING

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Abstract

Inspecting the IMS structural system tensioned together from precast reinforced concrete elements, considerable corrosion, in some cases rupture of the reinforcing tendons was found in the critical floor cross-sections. On the basis of the results of investigations carried out on a typical floor panel, assuming a corrosion predictable from disclosures, possibility of failure of the critical cross-section is 15 years after its construction by about two orders of magnitude higher than prescribed in the Hungarian Standard. Complete corrosion or rupture of the reinforcing tendons in either of the directions can lead to progressive collapse of the floor due to the rearrangement of stresses. Its prevention calls for structure strengthening.

Insufficient load bearing capacity of the floor structures — especially in the case of multielement systems — can be most favourably guaranteed by supplementary post-tensioning. Efficiency of the strengthening by post-tensioning depends essentially on the distribution of the normal force originating from the stressing force applied concentrically in the block floor ribs — that can be regarded as monolithic in respect of the supplementary stressing —, as well as on moments and reactions due to concentrated forces arising in consequence of the polygonal cable arrangement and acting perpendicularly to the floor plane.

For design the strengthening effect of subsequent steps of the post-tensioning and of the location of force application, the role of columns in stiffening, influence of the possible lattice models as well as the role of the 3.5 cm floor plate in stiffening and effect of joint eccentricity joint of structural elements have been investigated.

Keywords: precast waffle slab, post-tensioning, comparative lattice models.

Introduction

The IMS structural system tensioned together from precast reinforced concrete units is primarily fit for construction of dwellings and public buildings. The system was developed late in the 1950s in Yugoslavia, however, it has been used in several countries. In the original version, in every field, one precast 'waffle slab' unit is joined to the columns through the cut-outs at the edges by tensioning to the columns together in both directions after filling the jointgaps with a material rapidly hardening (*Fig. 1*).

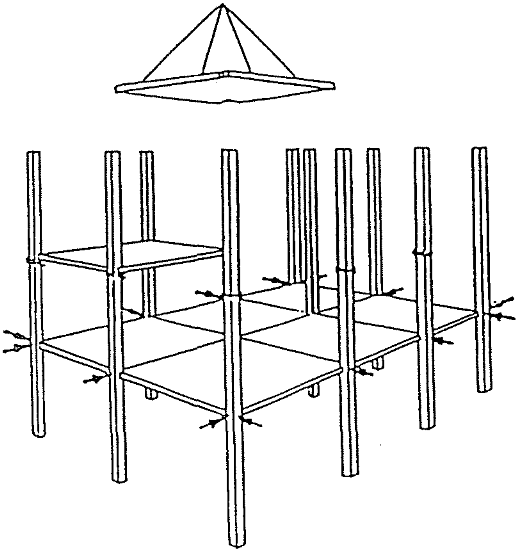


Fig. 1. The IMS construction system

Later the system has been developed by tensioning the floor panels together from several (two or four) precast floor units. Thus, larger column distances became possible, and floor elements are joined not only in the column lines but also in the middle of the panels. In this case, interaction of the waffle slab structure is provided by tension applied in both directions in the span-thirds, called secondary tensioning, in addition to the primary tensioning applied in the column lines.

In the system the horizontal and vertical connections of the structural units are characterized by post-tensioning in both cases, in the multielement system, also the bending capacity is guaranteed by the tensioning alone. Moment capacity is increased by polygonal cables.

Internal Forces of the Floor

Internal forces of the waffle slab structure supported in points in a regular arrangement by columns interacting due to tensioning can be determined e.g. by application of a lattice model by a computer program. In the computation, effect of the direction changes of the reinforcing tendons can be considered by concentrated external forces applied in the point of direction change and acting perpendicularly to the floor plane (FARKAS – GYÖRGYI – LOVAS – MISTÉTH, 1993).

Load Bearing Capacity Loss

Considerable corrosion of reinforcing tendons in cable channels concreted subsequently has been found recently in IMS buildings, mainly in floor to column joints. These failures threaten the load bearing capacity of the structure, therefore strengthening of this type of floors may become necessary (SZALAI, 1992).

Due to corrosion, efficiency of tensioning, thus, floor safety against rupture decrease. Although probability of load bearing capacity loss in the most stressed cross-section increases considerably due to the gradual decrease of the tension force of about 30% according to computations (FARKAS – GYÖRGYI – LOVAS – MISTÉTH, 1993), and surpasses the value of 10^{-4} prescribed in the Hungarian Standard, this does not mean automatically the collapse of the floor.

However, the experience shows that corrosion failures do not occur gradually. In several cases, rupture of reinforcing tendons was found even in some cross-sections of only several-year old buildings.

Rearrangement of internal forces due to rupture of the reinforcing tendons was investigated by the authors of the previously mentioned paper by the spatial lattice model. It was stated that in the case of rupture of reinforcing tendons of one of the directions in the column joint, the perpendicular moment of the same joint increased due to the rearrangement of the stresses, thus, probability of the progressive collapse of the floor considerably rises, i. e. strengthening of the structure becomes necessary.

Floor Strengthening by Post-Tensioning

Load bearing capacity of the floor structures failed — especially in the case of multielement systems — can be most favourably guaranteed by supplementary post-tensioning. By the use of tensioning strands in greased polyethylene tube, the corrosion effects by post-tensioning can be prevented. Supplementary tensioning can be arranged — in function of the building's destination — either in the blocks of the waffle slab or under the floor plane usually by polygonal strands (*Fig. 2*).

Friction-free tensioning by strands in greased polyethylene tube has been used recently throughout the world. It can be applied favourably both in the construction and strengthening of prestressed floors (FARKAS, 1993, MADARAS, 1993). In this case, the effect of the supplementary tensioning is advised to consider as external loads in form of concentrated forces acting in the anchoring points and break points of the reinforcing tendons for

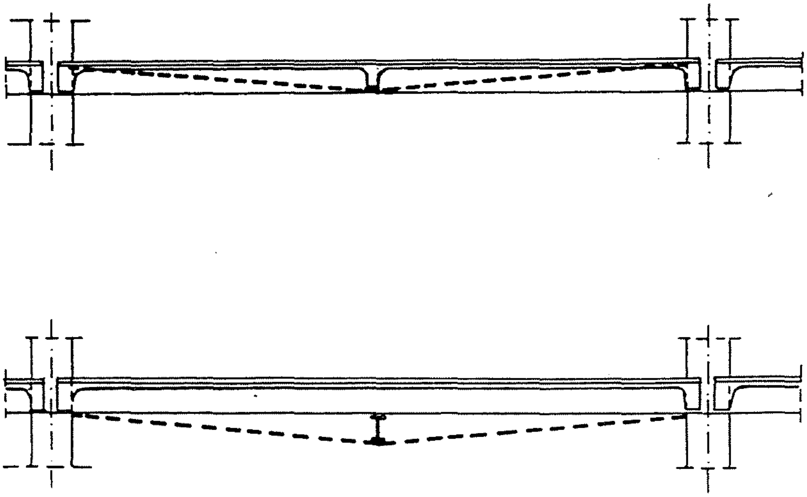


Fig. 2. Cable arrangement with one internal break point

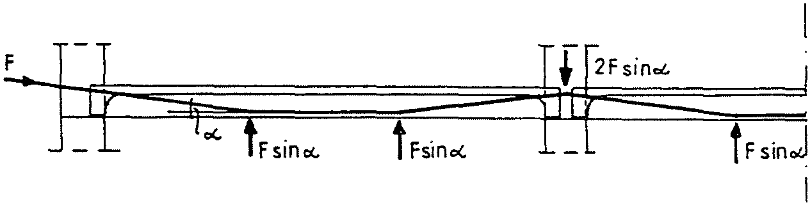


Fig. 3. Concentrated external forces equal to tension force

determination of the internal forces of the structure (*Fig. 3*) (Lacroix – Boutonnet – Orsat – Verde, 1992).

Computer Model of the Strengthening

Fig. 4 shows a unit of a four-element floor structure applied in a 6.0 × 6.0 m column arrangement. As the waffle slab units of different dimensions are of the same arrangement, mechanically it can be modelled by a grid system. The grid system will be solved statically by a spatial bar system program because in this way components of the stressing forces in the floor plane can be considered, consequently, in addition to bending moments and shear forces, also the normal forces can be computed.

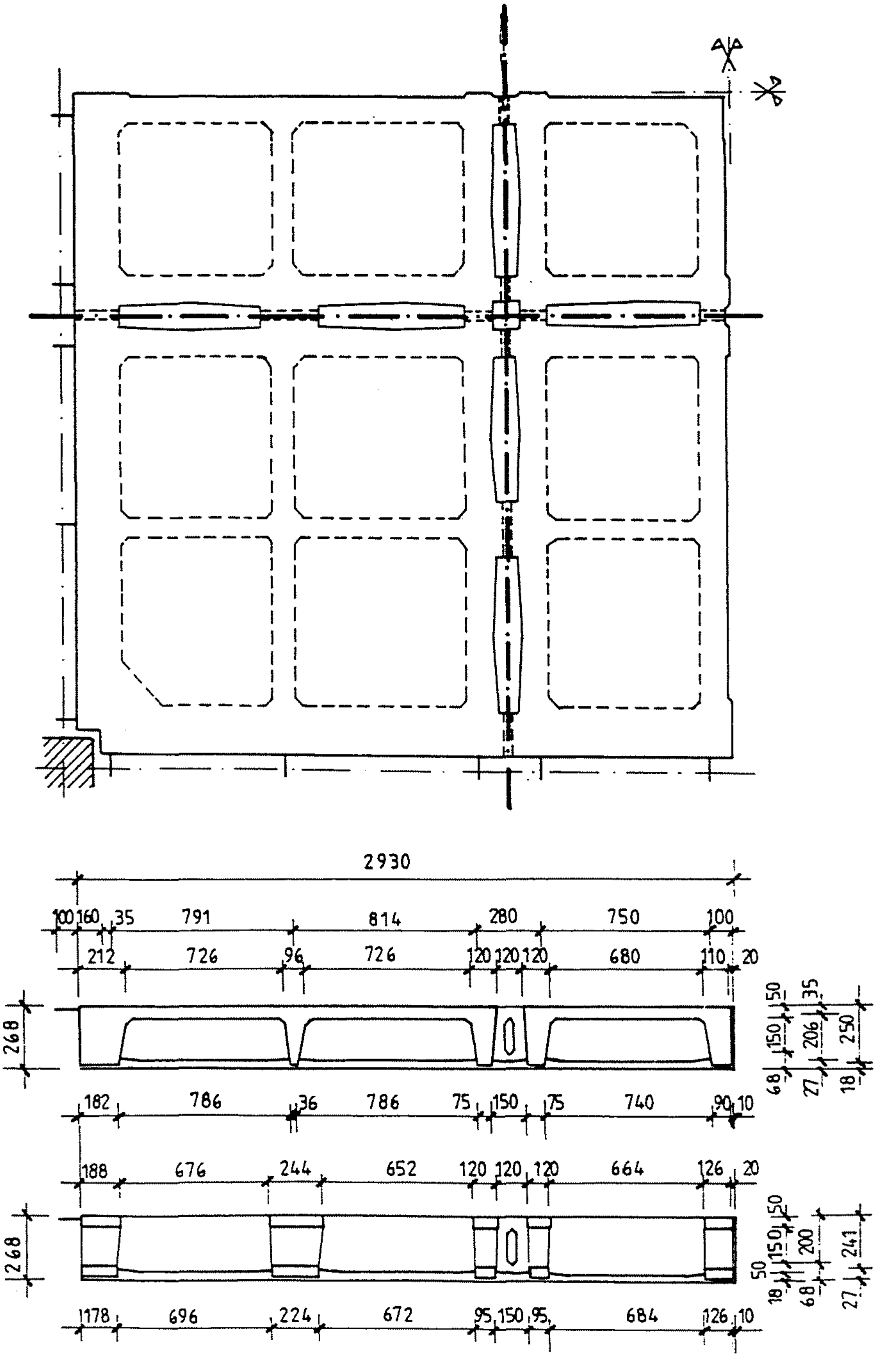


Fig. 4. Geometry of a precast unit

Parameter tests were carried out on a quarter of a fictious building of 18.0 × 42.0 m shown in *Fig. 5.*

Efficiency of the strengthening by post-tensioning essentially depends on the distribution of the normal force originating from the stressing force applied concentratedly in the waffle slab ribs — that can be regarded as monolithic in respect of the supplementary stressing —, as well as on moments and reactions due to concentrated forces arising in consequence of the zig-zag cable arrangement and acting perpendicularly to the floor plane.

Effect of the subsequent steps of the transverse post-tensioning, that of column stiffness, role of the location of force application, effect of the possible different lattice models as well as the role of the 3.5 cm floor slab in stiffening have been investigated. Test results are described in the following.

Comparison of the Possible Lattice Models

Distribution of post-tension forces introduced at the edges of the floor slab affects primarily the size of reaction force to be taken by friction in the floor to column joints. Normal force to be considered in the joint can be determined rather inaccurately, and it can be considerably influenced by the computation model applied. Therefore computations with different models were carried out for consideration of the effect of tensioning.

In the case of the spatial lattice model, degree of freedom in joints is 6, thus, for a large building, accurate consideration of the floor structure may be difficult, and data preparation for a complicated model is rather time consuming.

The most simple model only consists of ribs, the next one — containing again only vertical bars — takes the influence of the slab between the ribs into account by computing the cover plate ribs. In-plane stiffening role of the 3.5 cm slab can be modelled by transverse grids either according to the Hungarian Standard with a width six times the slab thickness ($6 \times v$) or with the equivalent cross-section parameters suggested by SZILÁRD, (1974). Diagonal stiffening bars can be either hinged or clamped to ribs. In addition, influence of eccentric joint of bars was investigated.

In any model, decrease of stresses computed from normal forces arising in ribs can be observed moving from the application spot of the tension force. Hinged or clamped joint of diagonal stiffening bars in model has no considerable influence (these effects cannot be depicted either) but eccentricity cannot be neglected.

The different models [1: Only vertical ribs; 2: Perpendicular cover plate ribs according to the Hungarian Standard; 3: Perpendicular cover

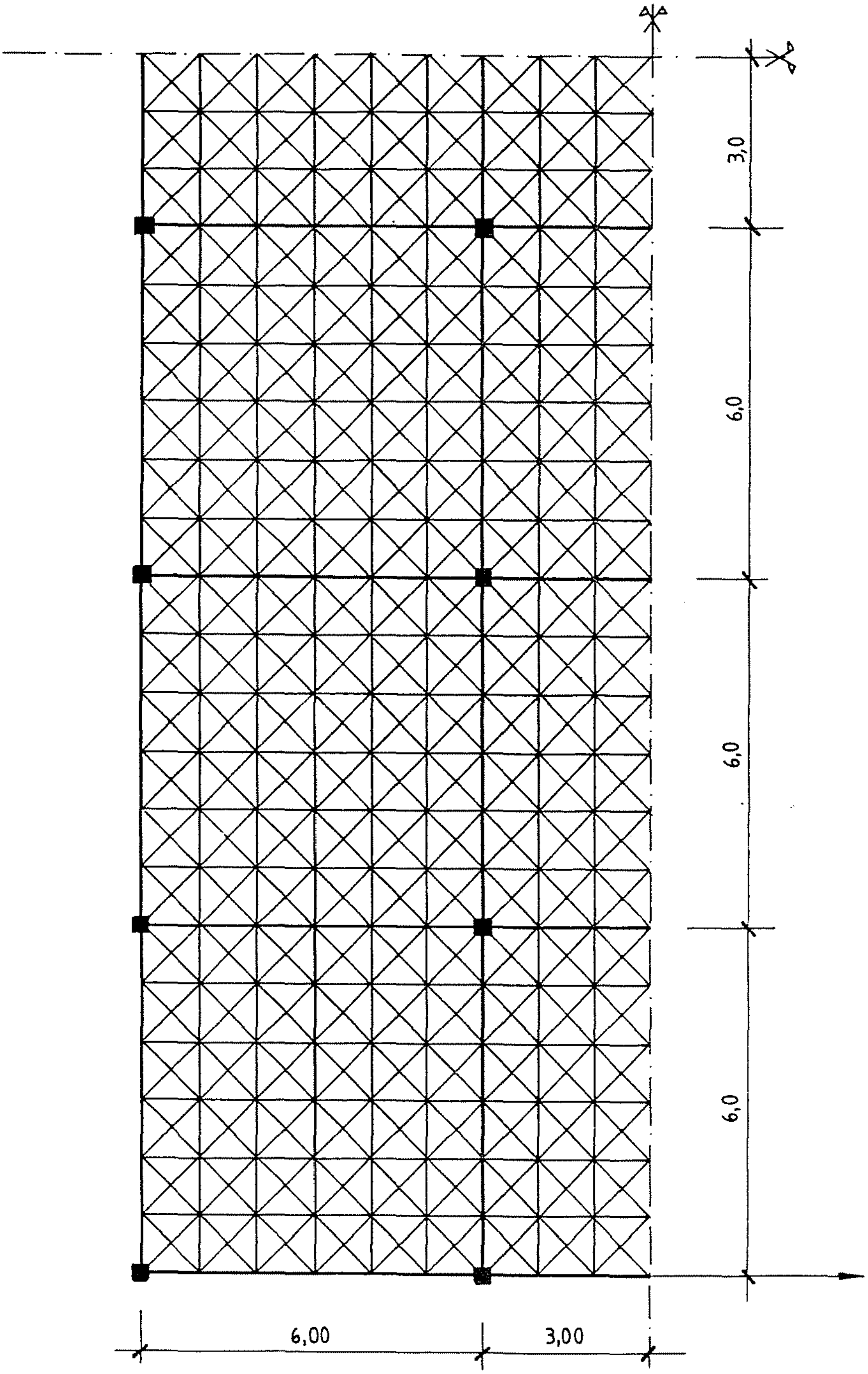


Fig. 5. Statical model of the building tested

plate ribs (according to the Hungarian Standard) + diagonal hinged bars of the width $6 \times v$; 4: Perpendicular cover plate ribs (according to the Hungarian Standard) + diagonal hinged bars of the width $6 \times v$ + eccentricity; 5: Perpendicular cover plate ribs (after Szilárd) + diagonal hinged bars (after Szilárd); 6: Perpendicular cover plate ribs (after Szilárd) + diagonal hinged bars (after Szilárd) + eccentricity; 7: Perpendicular cover plate ribs (according to the Hungarian Standard) + diagonal hinged bars (after Szilárd) + eccentricity] show an essential difference in the bending moments computed from the post-tensioning and the stresses computed from the normal force at the column lying farther from the introduction of the tension force. The most simple model fully neglecting the influence of the 3.5 cm slab therefore unfitted for modelling, but even the model containing only cover plate ribs overestimates the efficiency of the post-tensioning, $\approx 35 - -40\%$ in stresses and 15–20% in bending moments (*Fig. 6, Fig. 7*).

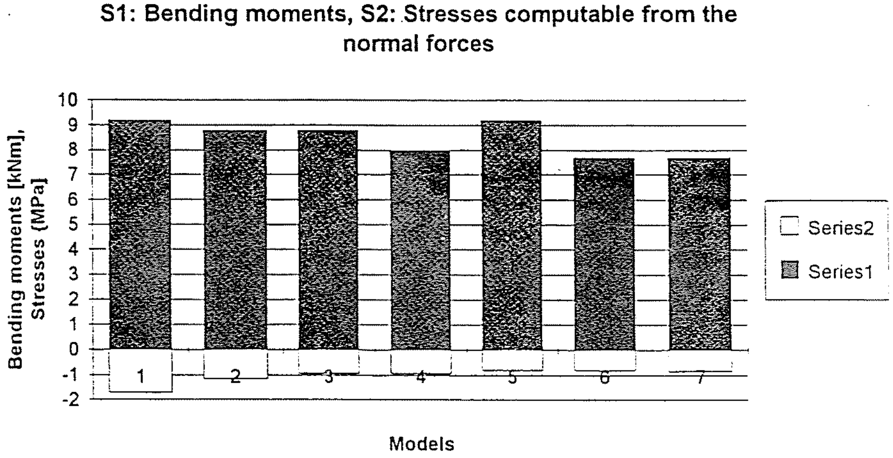


Fig. 6. Change of stresses computed from the normal force and bending moments in joints of the interim column and of the main rib

Summarizing, we can state that distribution of the tension force and the effect of the eccentric 3.5 cm floor plate can be followed only by a sophisticated model [proposed: Perpendicular cover plate ribs (according to the Hungarian Standard) + diagonal hinged bars (after Szilárd) + eccentricity; but of course, it may be a mixed model consisting of bars and flat shells].

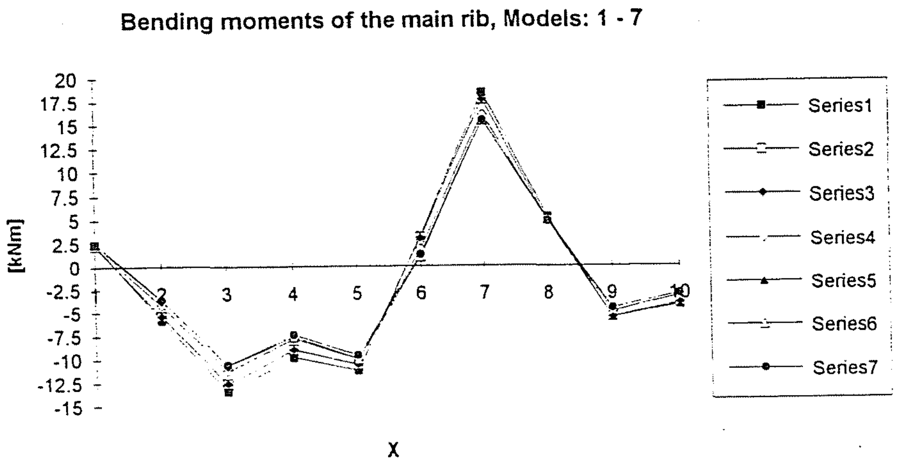


Fig. 7. Bending moments arising in the main rib in the cable's direction in the case of cable arrangement with two break points

Subsequent Steps of Stressing

Let us examine the distribution of the normal force due to the tension force introduced concentratedly, assuming that transverse tensioning occurs symmetrically right and left from the axis of symmetry of the building. Correspondingly, in four steps, formation of stresses computable from normal forces arising in ribs in direction of the cables are shown in *Figs. 8 a–d.* It reveals that influence of the particular steps of tensioning is considerable only in a zone of about 2 m of the columns, because of the considerable in-plane stiffness of the grid. Consequently, in practical point of view — in case of the usual 1–2 MPa specific post-tension force —, there is no essential accumulation, thus, sequence of the tensioning plays no particular role.

Supporting Effect of Columns

Columns can be regarded as clamped between the particular floor structures. From their displacement stiffness, a horizontal spring constant can be determined and this was added to the vertical point-like support as boundary condition. The examination aims at determination of the degree of decrease of the efficiency of tensioning by horizontal displacement stiffness coming away from the introduction spot of the tension force. Comparison of the stresses computed from normal forces of the ribs in cables'

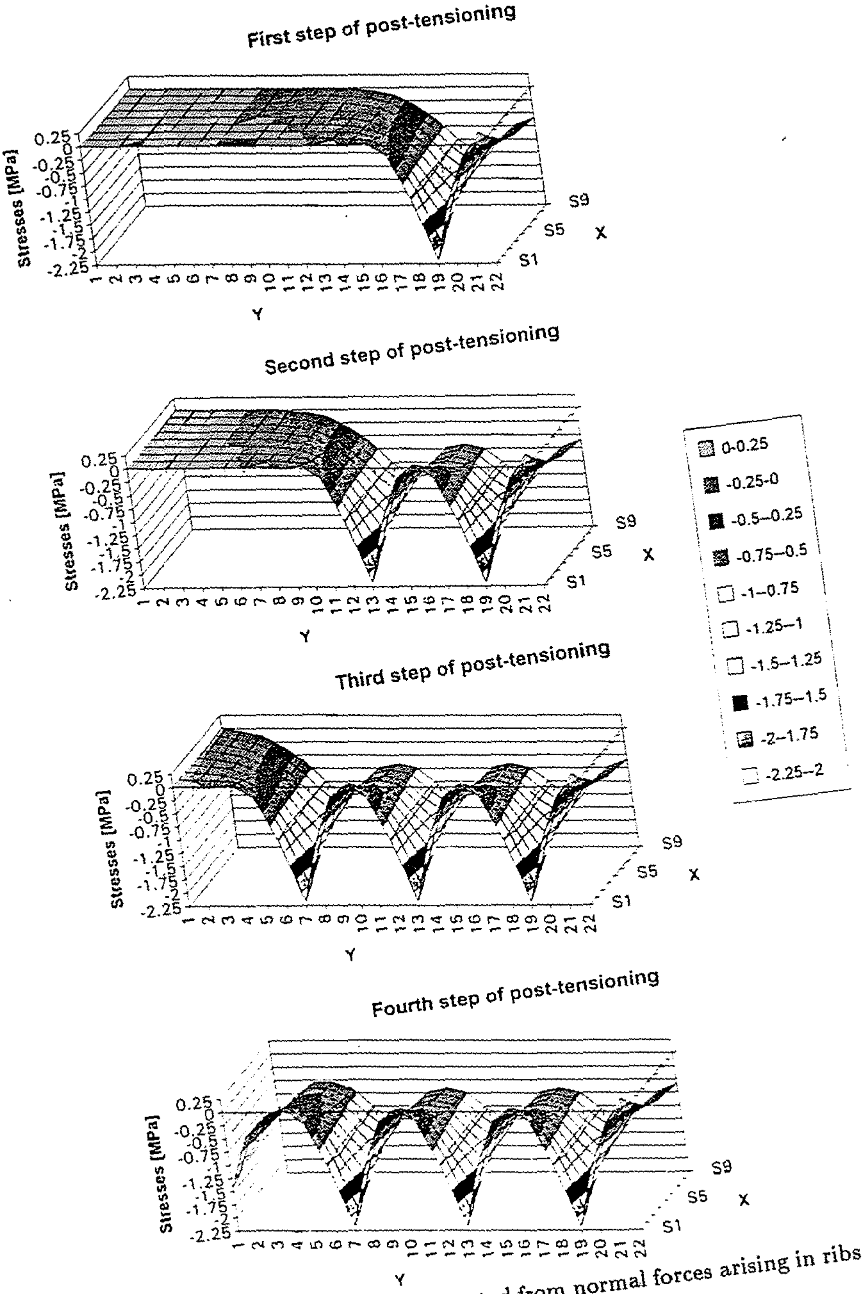
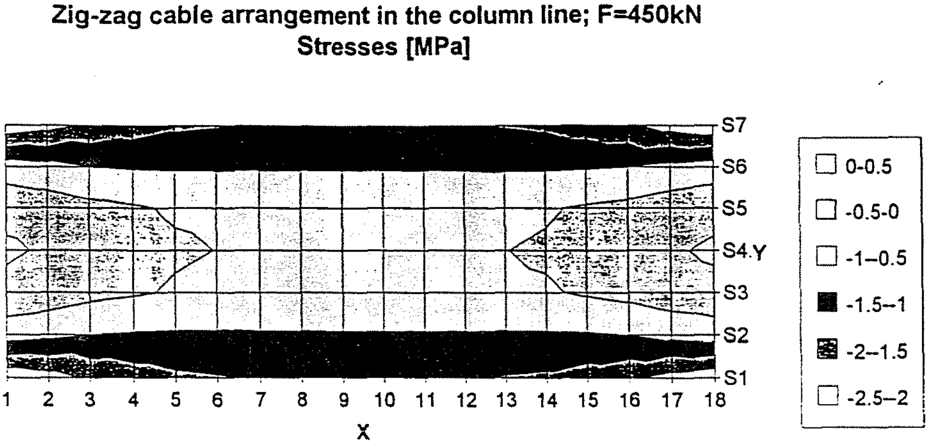
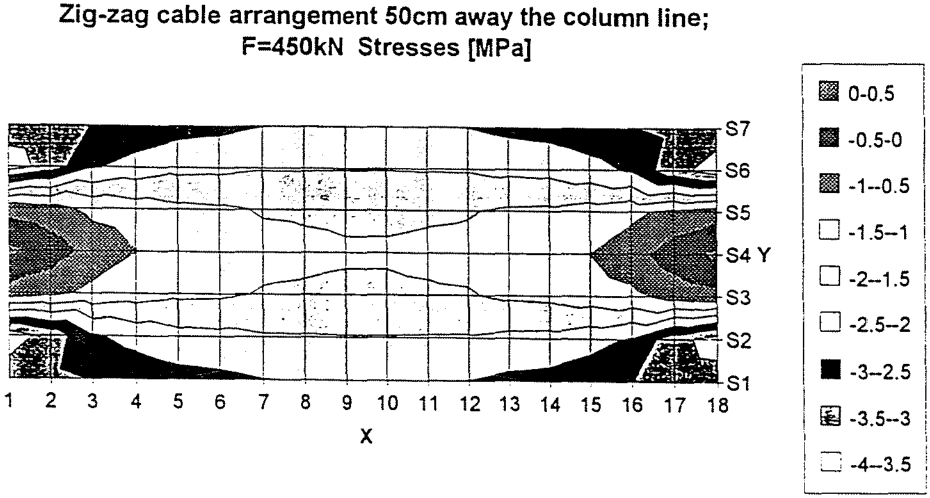


Fig. 8. Distribution of stresses computed from normal forces arising in ribs in the cables' direction after the particular steps of tensioning



Zig-zag cable arrangement in the column line; F=450kN Stresses [MPa]



Zig-zag cable arrangement 50cm away the column line; F=450kN Stresses [MPa]

Fig. 9. Distribution of stresses computed from normal forces arising in ribs in the cable's direction with zig-zag cable arrangement in the column line and 50 cm away from them

direction after the complete stressing of the building indicates that the role of columns in stiffening is about 3% so it is not essential.

Role of the Application Spot of the Tension Force and Arrangement of Cables in Straight or Broken Line

Distribution of stresses computed from normal forces arising in ribs in cables' direction is shown in *Fig. 9a* for the case of tensioning in the column lines and in *Fig. 9b* for tensioning at a distance of 50 cm from the columns. It can be stated that tensioning in the column lines yields less normal stress at the columns, which is less efficient due to the load transfer by friction.

Arrangement of cables in straight or broken lines practically does not affect distribution of normal stresses computable from normal forces, however, in respect of bending moment arising in the rib, the former arrangement is, of course, more efficient, and tension force loss due to corrosion can be added to.

References

FARKAS, GY. – GYÖRGYI, J. – LOVAS, A. – MISTÉTH, E. (1993): Load-Bearing Capacity of IMS Floors Affected by Cable Corrosion, *Periodica Polytechnica Ser. Civil Engineering*, Vol. 36, No. 3, pp. 271–282.

FARKAS, GY. (1993): Utófeszített monolit vasbeton födémlemezek tervezése, Kandidátusi értekezés.

LACROIX, C. – BOUTONNET, L. – ORSAT, P. – VERDE, P. (1992): La précontrainte des planchers de bâtiment par monotorons gainés graissés post-tendus, *Annales de l'I.T.B.T.P.* No. 509. Dec. 1992.

MADARAS, G. (1993): A szabadkábeles utófeszítés alkalmazási lehetőségei, *Magyar Építőipar*, 1993. No. 3.

SZALAI, K. (1992): IMS épületek szerkezeti rendszere, felülvizsgálata és megerősítése, Tanulmány, BME Vasbetonszerkezetek Tanszék.

SZILÁRD, R. (1990): Finite Berechnungsmethoden der Strukturmechanik, Ernst & Sohn, Berlin.