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A MINIMUM MATERIAL VOLUME BASED SHELL–PLATE–FRAME–PIPE SYSTEM

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Abstract. This paper describes a minimized material volume based shell–plate–frame–pipe system designed by the optimization technique of the Finite Element Method Computer System ANSYS 5.0A. The cylindrical shell and the frame of this system were connected with two polygonal plates. The pipes were connected to the corners of this frame. The movement of the upper end of the cylindrical shell was constrained in all directions except the direction of the applied force. The lower end of the shell was connected to the contour of the lower plate hole. The movement of the lower ends of the pipes were constrained in all directions at a fixed plane. The results of this paper can be used to design the working structure of a spinharrow.

Key words: soil processing machines, spinharrow, shell–plate–frame–pipe systems, finite element method, ANSYS 5.0A, design optimization.

1. INTRODUCTION

Spinharrow is a modern soil-processing machine. The term “spinharrow” is derived from the words “spin” and “harrow”. “Spin” is synonymous to “twist”, “turn”, “rotate”, “gyrate”, which express the movement characteristic of the working structure of a spinharrow. A harrow is a farm implement for cultivation, expressing the character of a task a spinharrow performs.

A spinharrow is a free active tillage machine, the working structures of which do not only move with its frame, but also relative to this frame. This relative motion is caused by the resistance forces of the soil. The working position of the working structure of a spinharrow is shown in Fig. 1, where the direction of the spinharrow’s motion is perpendicular to the plane of the figure. The working structures are clamped to the frame of the spinharrow under a small inclination angle. Typically, a spinharrow has 3–5 working structures.

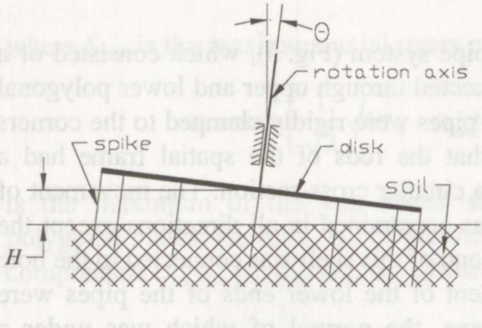

Fig. 1. The working position of the working structure of a spinharrow.

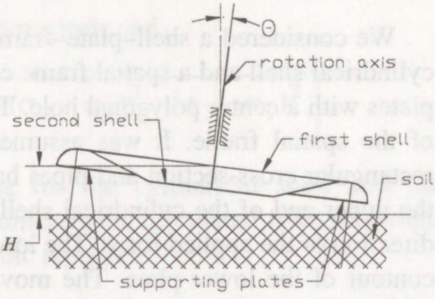

Fig. 2. Cross-sectional scheme of the working structure of a spinharrow designed by the *Estre Ltd*.

Reintam and Olt [1] from Estonian Agricultural University have studied the working structure of a spinharrow. They regard it as a homogeneous thick disk, with rigidly clamped spikes at the inner and outer circles of the disk. They realized the idea to level the ends of the spikes in the soil. Instead of a thick disk, the *Estre Ltd* constructed a disk consisting of connected shells and 12 supporting plates (Fig. 2) [2]. Such disks have a strong stress concentration at the points where the plates support the conical shell [2]. To decrease the stress concentrations, Heinloo [2] offered a construction of a disk of the working structure of a spinharrow containing two shells connected together (Fig. 3). Analysis of the stress state of such disks shows clearly that it is reasonable to construct at least a part of the disk of the working structure of a spinharrow as a frame. In [3] Heinloo and Olt studied the optimization of the stress state of a sandwich disk with spikes (Fig. 4) as a working structure of a spinharrow.

The authors of this paper have developed the idea of modelling the working structure of a spinharrow as a shell–plate–frame–pipe system with a minimum volume. To the knowledge of the authors, studies of analogous systems have not been published.

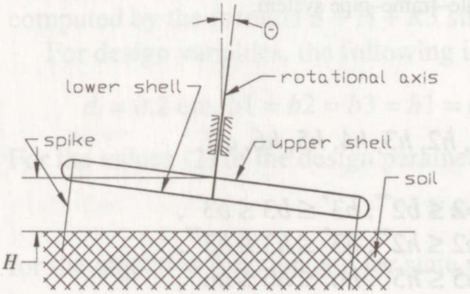

Fig. 3. Cross-sectional scheme of the working structure of a spinharrow designed by Heinloo and Olt [2, 3].

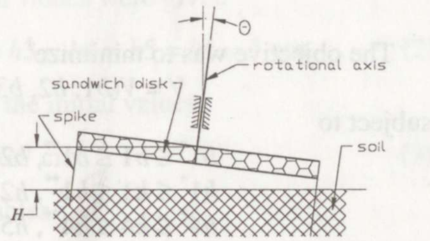

Fig. 4. Cross-sectional scheme of the working structure of a spinharrow as a sandwich disk with spikes.

2. STATEMENT OF THE PROBLEM

We considered a shell–plate–frame–pipe system (Fig. 5), which consisted of a cylindrical shell and a spatial frame connected through upper and lower polygonal plates with a centre polygonal hole. The pipes were rigidly clamped to the corners of the spatial frame. It was assumed that the rods of the spatial frame had a rectangular cross-section and pipes had a circular cross-section. The movement of the upper end of the cylindrical shell was constrained in all directions except the direction of the applied force. The lower end of this shell was connected to the hole contour of the lower plate. The movement of the lower ends of the pipes were constrained in all directions in the plane, the normal of which was under a certain inclination angle Θ to the rotation axis. In such a way, we modelled the loads of the working structure of a spinharrow just before the motion of the spinharrow in the direction of the applied forces.

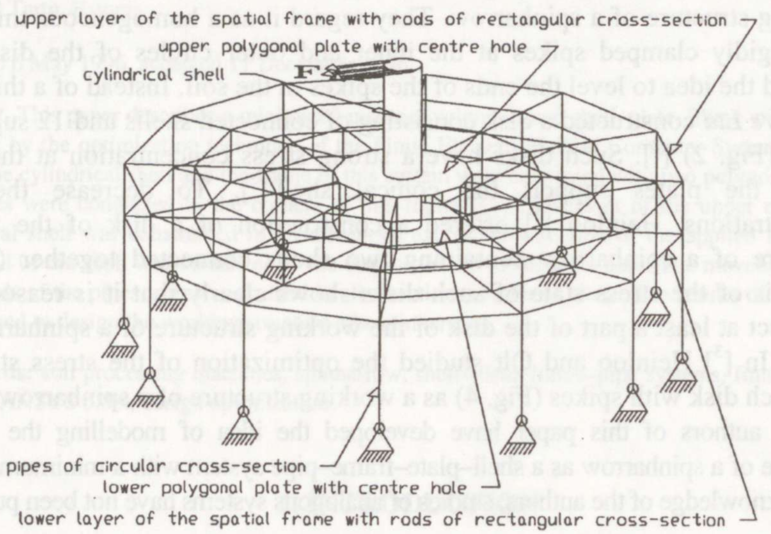

Fig. 5. The shell–plate–frame–pipe system.

The objective was to minimize[1]

$$V = V(b1, b2, b3, h1, h2, h3, h4, h5, h6, d_i)$$

subject to

$$b1^* \le b1 \le b1^{**},\ b2^* \le b2 \le b2^{**},\ b3^* \le b3 \le b3^{**},$$
$$h1^* \le h1 \le h1^{**},\ h2^* \le h2 \le h2^{**},\ h3^* \le h3 \le h3^{**},$$
$$h4^* \le h4 \le h4^{**},\ h5^* \le h5 \le h5^{**},\ h6^* \le h6 \le h6^{**},$$
$$d_i^* \le d_i \le d_i^{**},$$

[1] Notations are given at the end of the paper.

$$S_{max}{}^{*} \le S_{max} \le S_{max}{}^{**},\ \sigma^{*} \le \sigma \le \sigma^{**}, \quad (1)$$

where S_{max} is the maximum axial stress of frame rods and

$$\sigma = \max\left(\frac{1}{\sqrt{2}}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}\right)$$

is the maximum of the von Mises stress for the cylindrical shell and the polygonal plates. Here, σ_1, σ_2, σ_3 are the main stresses calculated from the stress components σ_x, σ_y, σ_z, σ_{xy}, σ_{xz}, σ_{yz} by the cubic equation

$$\begin{vmatrix} \sigma_x-\sigma & \sigma_{xy} & \sigma_{xy} \\ \sigma_{xy} & \sigma_y-\sigma & \sigma_{yz} \\ \sigma_{xz} & \sigma_{yz} & \sigma_z-\sigma \end{vmatrix} = 0.$$

The solution of the stated problem was obtained by the design optimization technique [4–7] of the Finite Element Method Computer System ANSYS 5.0A.

3. NUMERICAL VALUES OF THE PARAMETERS USED IN COMPUTATIONS

The following values of fixed parameters were used in the computations: $F = 4000$ N, $R1 = 2.45$ cm, $R2 = 9.5$ cm, $R3 = 37.7$ cm, $H = 11.2$ cm, $S = 5$ cm, $\Theta = 3^{o}$, $d_e = 1.8$ cm, $d_i^{*} = 0$ cm, $b1^{*} = b2^{*} = b3^{*} = h1^{*} = h2^{*} = h3^{*} = h4^{*} = h5^{*} = h6^{*} = 0.1$ cm, $S_{max}{}^{*} = 1.5{\cdot}10^{8}$ Pa, $\sigma^{*} = 0.4{\cdot}10^{8}$ Pa, $d_i^{**} = 1.7$ cm, $b1^{**} = b2^{**} = b3^{**} = h1^{**} = h2^{**} = h3^{**} = h4^{**} = h5^{**} = h6^{**} = 5$ cm, $S_{max}{}^{**} = 2{\cdot}10^{8}$ Pa, $\sigma^{**} = 2{\cdot}10^{8}$ Pa, $E = 2{\cdot}10^{11}$ Pa, $\nu = 0.3$.

The radii of intermediate polygons of the spatial frame layers were computed by the formulae: $(R3 - R2)/3$ and $2\,(R3 - R2)/3$. The distances of the constrained circular rod points from the upper layer plane of the spatial frame were computed by the formula $S + H + R3 \sin[30\,(i-1)] \sin\Theta$, $i = 1, 2,....,12$.

For design variables, the following initial values were given:

$$d_i = 0.2 \text{ cm},\ b1 = b2 = b3 = h1 = h2 = h3 = h4 = h5 = h6 = 1 \text{ cm}. \quad (2)$$

For the values (2) of the design parameters, the initial values

$$V = 3126.7 \text{ cm}^3 \quad (3)$$

for the objective function and for state variables

$$S_{max} = 1.57{\cdot}10^{8} \text{ Pa}, \qquad \sigma = 0.159{\cdot}10^{8} \text{ Pa} \quad (4)$$

were computed. Note that the initial value of σ did not satisfy the constraints (1).

4. COMPUTATION RESULTS

The ANSYS 5.0A optimization process was converged to a local optimum after 256 iterations. The computed optimal values of the design variables were:

$$d_i = 0.1 \text{ cm}, b1 = 0.89 \text{ cm}, b2 = 0.46 \text{ cm}, b3 = 0.94 \text{ cm},$$

$$h1 = 0.15 \text{ cm}, h2 = 2.92 \text{ cm}, h3 = 1.62 \text{ cm}, h4 = 0.13 \text{ cm}, \quad (5)$$

$$h5 = 0.12 \text{ cm}, h6 = 0.31 \text{ cm}.$$

The optimal value of the objective function was

$$V = 2206.3 \text{ cm}^3. \quad (6)$$

The values

$$S_{max} = 1.95 \cdot 10^8 \text{ Pa}, \sigma_{max} = 0.563 \cdot 10^8 \text{ Pa} \quad (7)$$

of optimal shell–plate–frame–pipe system state variables satisfy the required constraints (1).

Note that the optimal value (6) of the objective function V is 29% lower than the initial value. Under restrictions (1), the values of $|\max S_{max}|$ and σ for the optimal values (5) of the design variables are 242 and 254% higher than the initial values (2), respectively.

The von Mises stress distribution on the external surface of the cylindrical shell and on the upper surface of the lower polygonal plate are shown in Figs. 6 and 7 at the optimal (*a*) and initial (*b*) states. From Fig. 6 we can conclude that the distribution of the von Mises stress on the external surface of the cylindrical shell at the optimal (5) (*a*) and initial (2) (*b*) values of design variables is quite different. For the optimal values (5) of the design variables, the state variable σ value on external surface of the cylindrical shell was 254% higher than the initial value. Figure 7 shows that the von Mises stress distribution on the upper surface of the lower polygonal plate at the optimal (*a*) and initial (*b*) configurations is similar, but its values are very different. For the optimal values (5) of the design variables, the state variable σ values on the upper surface of the lower plate were for 1366% higher than the initial values.

The maximum axial stress S_{max} distribution in frame rods is shown in Figs. 8 and 9 for the optimal (5) and the initial (2) values of the design variables. It is demonstrated that the distribution and the values of maximum axial stress in frame rods are quite different. For the optimal values (5) of the design variables, the value of $|\max S_{max}|$ is 242% greater than the corresponding initial value.

By ANSYS 5.0A optimization technique [4–7], we found the values for the design variables which guarantee by the redistribution of the stress the local minimum for the volume of the considered shell–plate–frame–pipe system. The other local minimum for this volume can be found for new initial values of the design variables.

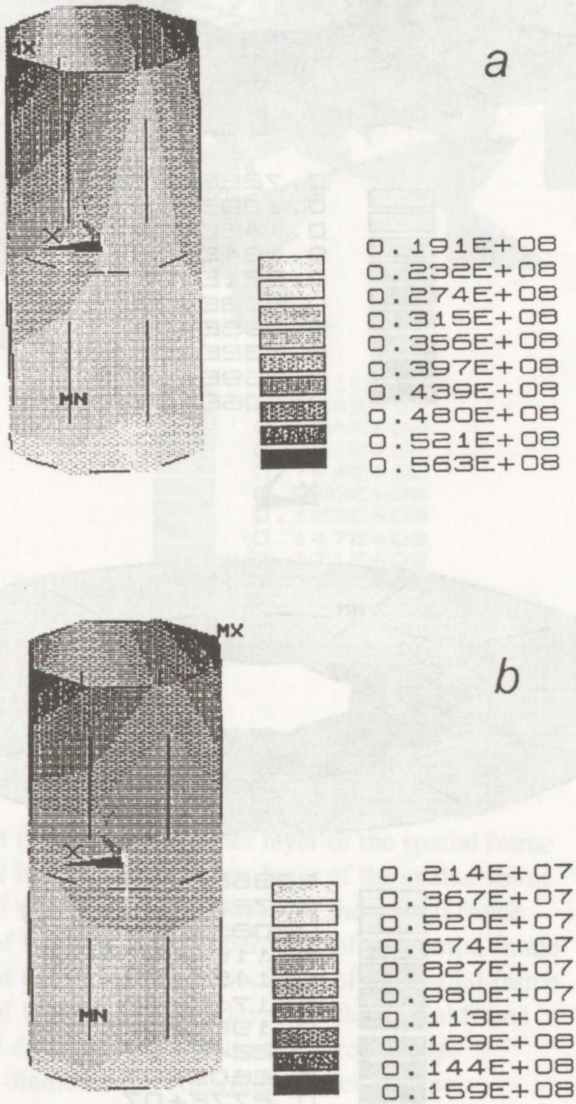

Fig. 6. Distribution of the von Mises stress on the external surface of the cylindrical shell at the optimal (*a*) and initial (*b*) values of design variables.

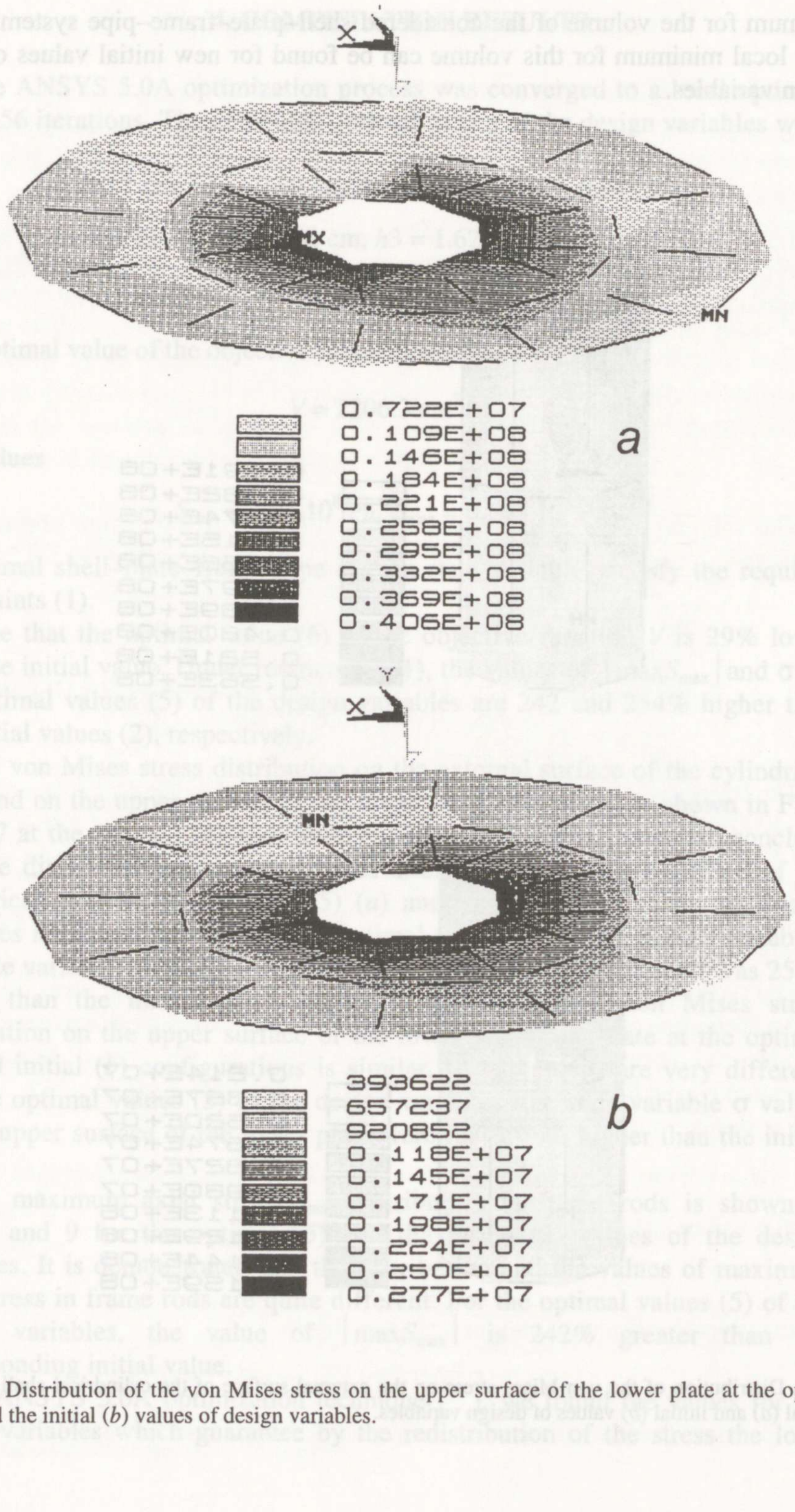

Fig. 7. Distribution of the von Mises stress on the upper surface of the lower plate at the optimal (*a*) and the initial (*b*) values of design variables.

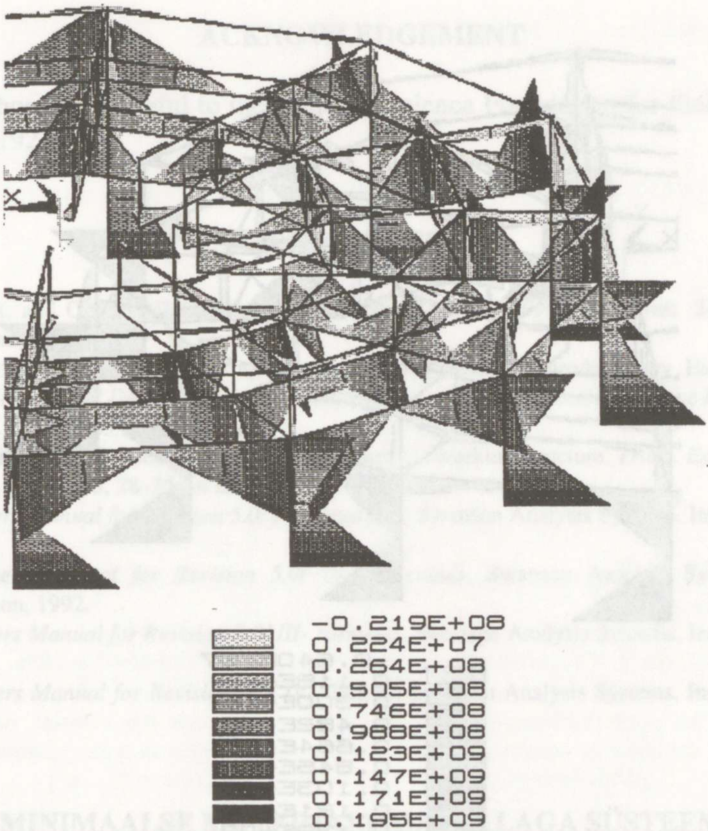

Fig. 8. The maximum axial stress (S_{max}) distribution in frame rods and pipes at the optimal values of design variables.

NOTATIONS

$b1$	width of the rods at the upper layer of the spatial frame
$b2$	width of the rods at the lower layer of the spatial frame
$b3$	width of the rods between layers of the spatial frame
$h1$	height of the rods at the upper layer of the spatial frame
$h2$	height of the rods at the lower layer of the spatial frame
$h3$	height of the rods between layers of the spatial frame
d_e	external diameter of a constrained circular pipe
d_i	internal diameter of a constrained circular pipe
$h4$	wall thickness of a cylindrical shell
$h5$	thickness of a lower polygonal plate
$h6$	thickness of an upper polygonal plate
F	total load of the cylindrical shell
E	modulus of elasticity

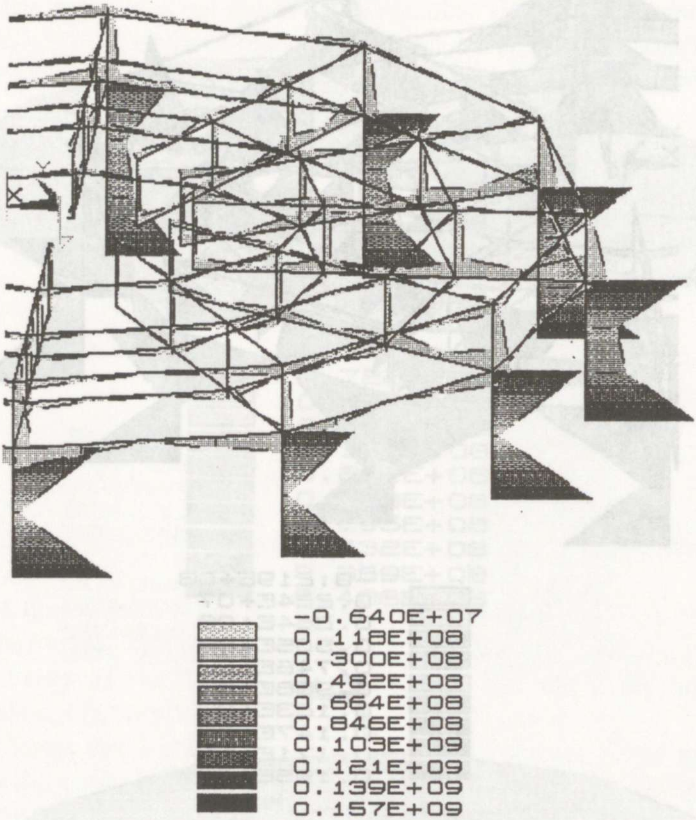

Fig. 9. The maximum axial stress (S_{max}) distribution in frame rods and pipes at the initial values of design variables.

σ	maximum of the von Mises stress for the cylindrical shell and polygonal plates
S_{max}	maximum axial stress of frame rods and pipes
ν	Poisson's ratio
$R1$	radius of the cylindrical shell
$R2$	external radius of the polygonal plate
$R3$	radius of the upper and lower layers of the spatial frame
H	distance between the centre of the upper polygonal plate and the plane where the motion of circular pipes is constrained
S	distance between spatial frame layers
Θ	inclination angle.

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MINIMAALSE MATERJALI RUUMALAGA SÜSTEEM KOORIK–PLAAT–SÕRESTIK–TORU

Mati HEINLOO ja Kaspar KAUL

On esitatud süsteemi koorik–plaat–sõrestik–toru materjali ruumala minimeerimise tulemused. Vaadeldava süsteemi silindriline koorik ja sõrestik on omavahel seotud kahe tsentraalse polügonaalplaadi abil, kummagi keskel polügonaalne auk. Sõrestiku nurkadesse on kinnitatud torud. Kooriku ülemine ots saab liikuda vaid jõu mõjumise suunas. Kooriku alumine ots on kinnitatud alumise plaadi augu serva külge. Torude alumised otsad ei saa fikseeritud tasapinnal liikuda. Materjali ruumala minimeerimiseks on kasutatud lõplike elementide meetodit realiseeriva arvutisüsteemi ANSYS 5.0A optimeerimistehnikat. Käesoleva töö tulemusi saab kasutada vurräkke projekteerimisel.