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Geometric Modeling of Coating Shells and Calculations of their Bearing Capacity

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Abstract

Based on the generalization of the theory of generalization of polyhedra, a method for linearizing the yield conditions of an arbitrary form, for plastic shells by inscribed and circumscribed hyperpolyhedra, has been developed. The technique allows one to obtain hyperpolyhedra with an arbitrary number of faces. The linearization technique is used to construct an algorithm and a program for automatic approximation of convex hypersurfaces by inscribed and circumscribed hyperpolyhedra with any number of faces. Automatic linearization of plasticity conditions for rigid-plastic shells made it possible to construct an effective method and PPP for calculating lower estimates for the bearing capacity of shallow shells with rectangular plan. The possibility of increasing the efficiency of programs due to the optimal choice of the number of faces of hyperpolytopes is obtained - polyhedra with a minimum number of faces are found, leading to estimates of the bearing capacity with a given accuracy. On the basis of the kinematic method of the theory of limit equilibrium and the use of the generalized Ioganson's yield condition, a method has been developed for calculating the bearing capacity of plates of a complex shape.

Keywords: Geometric modelling; bearing capacity; yield conditions; approximation; hypersurface; polyhedron; equilibrium; hyperpolyhedron; seismic resistance; design; plasticity theory; design; geometric modelling; rigid plasticity; six-dimensional space; surface; linearization; ultimate load; deformation; optimization; coefficient

Introduction

The bearing capacity of structures is determined by the methods of the theory of limit equilibrium. This theory is the most developed section of the applied theory of plasticity.

The most important initial prerequisites for the theory of limit equilibrium are the assumptions:

a) about the ideal plasticity of the material;
b) linear deformation of the shell.

In most real shells, both requirements are met and the application of the theory of limit equilibrium can be considered justified.

The theory proceeds from two theorems - static and kinematic. The first one defines the limit load as the largest of all loads for which the equilibrium and limit conditions are still satisfied. The second theorem defines the ultimate load as the smallest of all loads at which the shell is already transformed into a variable system.

The static theorem estimates the ultimate load from below, and the kinematic one from above.

The theory of limit equilibrium makes it possible to move from one-parameter calculations with the bearing capacities of shells to optimization problems. Here, the most important factors affecting the bearing capacity and the material consumption of the structure are the shape of the average surface, density and other characteristics.

The practice of real design is usually given the radius of the plan of the overlapped area and the value of the required bearing capacity. The main parts of the optimization problem are the quality criterion, the design area and constraints that are functional in nature. Minimization of a criterion in a given area under constraints is an optimal design problem and coincides in form with a standard problem of geometric modeling of computer programming.

It is known [1, 2] that the shape of the yield surface has a limited effect on the estimate of the ultimate load; in this work, when choosing a method for constructing polyhedra, it was assumed that the load-bearing capacity of the shell weakly depends on the shape of the polyhedra faces. In this case, the main attention is paid to the development of partitioning procedures, the same for inscribed and circumscribed polyhedra and range, this method can be applied not only to smooth, but also to piecewise-smooth yield surfaces with edges and vertices.

The ways to effectively implement reserves in construction is to refine the methods of calculation and design schemes for structures and structures at all stages of design, as a result of which savings in materials are ensured while maintaining the reliability and safety of buildings and structures.

The complexity of calculations of building structures, of course, lengthens the design time, which in turn negatively affects the time for commissioning construction projects and facilities.

In connection with the tasks set by the government in our country, targeted programs have been developed and approved in the field of improving design and estimate work and improving building structures, in particular, the targeted scientific and technical program of Uzgostroy of Uzbekistan up to 30 years.

This article was written in accordance with this program: "To develop, based on the theory of plasticity, strength and stability, proposals for the choice of design schemes and recommended methods for calculating buildings and structures of mass use."

Thus, the article, which discusses the geometric aspects of strength calculations and the design of effective modern spatial structures, is very relevant. The problem of the reliability of buildings and structures while reducing their materials-capacity, and hence the cost, is closely related to the assessment of their bearing capacity. The issues of stability and reliability of buildings and structures are of particular importance during construction in areas with elevated seismicity, in particular, in the republics of Central Asia. The solution of this problem is largely facilitated by the use in modern construction of projects in which monolithic shells of conventional flat coatings are offered as building coatings. At the same time, the cost of 1 m2 of the building cover is reduced by 8,000-10,000 sums, steel consumption by 12-32 kg, the weight of the cover is up to 40% compared to solutions in planar structures. It is known that in seismic regions, especially in Central Asia, due to the need to ensure seismic resistance at the lowest cost of building materials while increasing the seismic resistance of the coating.

Nonlinear functions of many variables have found application in various branches of science and technology. The most typical example is a variety of objective functions of optimization problems. In the general case, their solution is reduced to a non-linear programming problem, but often the geometric analysis of non-linear functions allows one to linearize them in order to further use well-developed linear programming methods.

As another class of problems, consider the problem of the carrying capacity of shells. The search for two-sided estimates of the bearing capacity of ideal rigid-plastic structures by static and kinematic methods of the theory of limit equilibrium in the classical form is associated with the condition of plasticity as a function of many variables (Fig. 1).

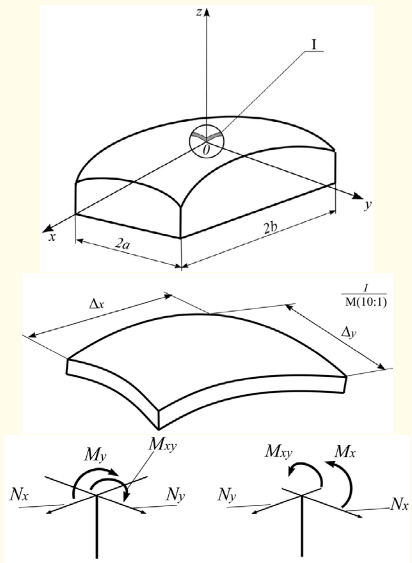

Figure 1: Internal forces of coating shells.

$$F\,(N_x, N_y, N_{xy}, M_x, M_y, M_{xy}) \leq K \qquad (1)$$

The most natural method for studying a function of this kind is geometric modeling in a multidimensional space.

For shells, the plasticity condition is usually formulated in the six-dimensional space of internal forces $N_{i,j}$, $M_{i,j}$ and in the general case ***G*** is a closed convex hypersurface of the second order. Due to the convexity of ***G***, the problem of calculating the bearing capacity of shells is essentially nonlinear.

The real design of structures is associated with their optimization. Environments of various optimization formulations (1) from a practical point of view, the problem of finding structures of the lowest conditional cost (mass) for a given bearing capacity is of the greatest interest. Such a statement of the problem requires a multiple solution of the problem of limit equilibrium, therefore, high requirements are imposed on the algorithm for finding the bearing capacity in terms of speed.

One of the most effective ways to speed up the solution of this problem is to linearize the original nonlinear problem, then linear programming methods can be applied to solve it. Such a linearization requires the replacement of a nonlinear convex hypersurface by inscribed or circumscribed polyhedra (hyperpolyhedra) [2, 8].

It is known [1, 6] that the estimate obtained on the basis of the exact plasticity surface lies between the estimates found using the outer and inner approximations, so the geometric interpretation of this problem is to choose a hyperpolytope that guarantees the given accuracy of the solution.

Such problems are part of the general geometric problem of discretization of a hypersurface in order to linearize the non-linear function that describes it. Proceeding from this, in this paper we consider methods and algorithms for approximating second-order hypersurfaces by inscribed and circumscribed hyperpolyhedra.

To achieve a given approximation accuracy, the step is the control parameter. Indeed, for a two-sided estimate of the approximation error, it is necessary to determine the coordinates of the vertices of a circumscribed or inscribed hyperpolytope.

When approximating a hypersurface in E^n space, such vertices are the intersection points of the corresponding tangents or secants of the hyperplane.

Let a hypersurface be given by a control of the form:

$$F\,(x^I, x^{II}, \dots, x^n) = 0$$

$$\sum_{i=1}^{n} (x^i a_i^{-1})^2 = 1 \qquad (2)$$

then the tangent hyperplane can be represented in the following form:

$$\sum_{i=1}^{n} \frac{\partial F}{\partial x_j^i}\left(x^i - x_j^i\right) = 0 \qquad (3)$$

where, x^I :=x, x^{II}:=y, x^{III}:=z,… mutually perpendicular axes E^n space i.e. current coordinates, $\frac{\partial F}{\partial x_j^i}$, $\frac{\partial F}{\partial x_j^{II}}$, …., $\frac{\partial F}{\partial x_j^n}$ - corresponding value of partial derivatives.

Differentiating equation (2) we obtain:

$$\left.\frac{\partial F}{\partial x_j^i}\right|_{x^i = x_j^i} = 2x_j^i a_j^{-2}; \quad i=I,\ II,\ III, \dots n, \quad j=1,\ 2,\ 3, \dots n$$

then the desired equation has the form:

$$\sum_{j=1}^{n} x_j^i \ a_i^{-2}\ (x^i - x_j^i) = 0$$

or

$$\sum_{i=1}^{n} \frac{\partial F}{\partial x_j^i} - (\sum_{j=1}^{n} (x_j^i\ a_j^{-1})^2 = 0 \qquad (4)$$

From (4) we can determine the coefficients of the main faces of the hyperpolyhedron:

$$A_j^i = \alpha_j^{-2} x_i^i\ ; \quad -A_j^{n+1} = \sum_{j=1}^{n} (x_j^i\ \ \alpha_j^{-1})^2 \qquad (5)$$

Examples of approximations by inscribed and circumscribed hyperpolytopes are illustrated in [8].

The calculation of the coefficients of hyperplanes, which are the main faces of the circumscribed and inscribed hyperpolyhedra, are given in Tables 1 and 2.

Plane numbers	***Coefficients of inscribed hyperpolyhedra***			
	A^{I}	A^{II}	A^{III}	A^{IV}
1	0,21333	-0,07514	0,36872	-0,21386
2	0,25625	0,01025	0,50663	-0,29384
3	0,17674	0,17674	0,58628	-0,34004
4	0,10125	0,25625	0,50663	-0,29384
5	0,07514	0,21333	0,36872	-0,21386

Table 1

Plane numbers	***Coefficients of circumscribed hyperpolyhedra***			
	A^{I}	A^{II}	A^{III}	A^{IV}
1	0,07963	-0,01750	0,33226	-0,19271
2	0,05829	0,05829	0,43943	-0,25487
3	0,0175	0,07963	0,33226	-0,19271
4	0,27187	-0,05976	0,19463	-0,27254
5	0,19902	0,19902	0,25741	-0,36044
6	-0,05976	0,27187	0,19463	-0,27254

Table 2

The error δ is defined as the distance between circumscribed and inscribed hyperplanes i.e.

$$|\delta_j| = (\sum_{j=1}^{n} A^i\, x_j^i + A^{i+1}) * \left(\sum_{i=1}^{n} (A^i)^2\right)^{-0,5} \qquad (6)$$

The value δ of the approximation error is assumed to be $\delta = \delta_j\ (max)$. This error decreases with an increase in the number of hyperplanes selected from plane bundles.

In this work, hyperpolytopes with a minimum number of faces are searched for, leading to a given accuracy of solving the limit equilibrium problem. Since in this case it is necessary to consider a different shape and a different number of faces, the basis of the work is the procedure for automatically constructing convex hyperpolytopes inscribed and circumscribed around a certain hypersurface, as well as the automatic formation of the matrix of a linear programming problem.

It is known [1.8 pp. 150-151] that the estimate obtained on the basis of the exact yield surface lies between the estimates found using the external and internal approximations. Then we can interpret it as choosing a hyperpolytope that guarantees a given accuracy of the solution. Naturally, an increase in the number of faces improves the approximations of the exact surface, but at the same time the size of the linear programming problem increases significantly. Consequently, hyperpolytopes with a minimum number of hyperfaces are also searched here, leading to a given accuracy of solving the problem of limit equilibrium (Fig. 2).

As an example, the von Mises yield condition is chosen, without instant setting.

Below are the results of calculations of the lower limit of the uniform ultimate load for a different number of faces of the inscribed (line I) and circumscribed (line II) hyperpolyhedra. For the calculation, an appeal is made to the library subroutine of linear programming SIMPLEX.

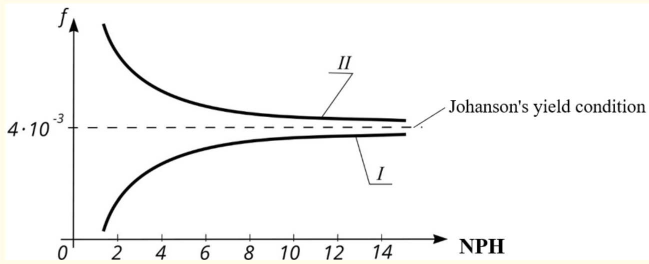

Figure 2: Number of points belonging to hyperfaces (NPH).

The lower estimates of the bearing capacity of the shell obtained here suggest that in most practical calculations an acceptable accuracy can be achieved even with a small number of hyperfaces. In this case, the guarantee of reliability is the simultaneous construction of the inscribed and circumscribed hyperpolyhedra.

Conclusions

Thus, the following conclusions can be drawn.

1. Based on the generalization of the theory of generalization of polyhedra, a method for linearizing the yield conditions of an arbitrary form has been developed, for plastic shells by inscribed and circumscribed hyperpolyhedra. The technique makes it possible to obtain hyperpolyhedra with an arbitrary number of faces.
2. The linearization technique was used to construct an algorithm and a program for automatic approximation of convex hypersurfaces by inscribed and circumscribed hyperpolyhedra with any number of faces.
3. Automatic linearization of plasticity conditions for rigid-plastic shells made it possible to construct an effective method and *PPP* for calculating lower estimates for the bearing capacity of shallow shells with rectangular plan. The possibility of increasing the efficiency of programs due to the optimal choice of the number of faces of hyperpolytopes is obtained - polyhedra with a minimum number of faces are found, leading to estimates of the bearing capacity with a given accuracy.
4. On the basis of the kinematic method of the theory of limit equilibrium and the use of the generalized Ioganson's yield condition, a method has been developed for calculating the bearing capacity of plates of a complex shape.
5. The peculiarity of the technique and its difference from previous results is the use of logical *R*-functions for constructing curved surfaces of plates based on the outer and inner contours of a complex shape.

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