



**DRUŠTVO ZA ISPITIVANJE I ISTRAŽIVANJE  
MATERIJALA I KONSTRUKCIJA SRBIJE**



**UDRUŽENJE SAVREMENE INDUSTRIJE  
GLINENIH PROIZVODA SRBIJE**



**INSTITUT ZA ISPITIVANJE  
MATERIJALA IMS - BEOGRAD**

## **XXVIII KONGRES DIMK I IX KONGRES SIGP**

**SA MEĐUNARODNIM SIMPOZIJUMOM  
O ISTRAŽIVANJIMA I PRIMENI SAVREMENIH DOSTIGNUĆA U  
GRAĐEVINARSTVU U OBLASTI MATERIJALA I KONSTRUKCIJA**

## **XXVIII CONGRESS DIMK AND IX CONGRESS SIGP**

**WITH INTERNATIONAL SYMPOSIUM  
ON RESEARCHING AND APPLICATION OF CONTEMPORARY  
ACHIEVEMENTS IN CIVIL ENGINEERING IN THE FIELD OF  
MATERIALS AND STRUCTURES**

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U OBLASTI MATERIJALA I KONSTRUKCIJA**

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**PARAMETRIČKI ALGORITAM ZA ODREĐIVANJE OBLIKE DVOSLOJNIH  
LJUSKI PODLOŽNIH SEIZMIČKOM OPTEREĆENJU**

**Rezime:** Kada su izložene horizontalnim seizmičkim silama, geometrija ljuski igra ključnu ulogu u njihovom ponašanju, prvenstveno zbog njihove lake mase i velike geometrijske krutosti. Dosadašnja istraživanja su pokazala da se definicija oblika ljuski zasniva na trodimenzionalnim mrežastim modelima dobijenim pomoću algoritama dinamičke relaksacije, uzimajući u obzir sopstvenu težinu ljuske i horizontalnu seizmičku silu koja deluje u najmanje dva ortogonalna pravca. Primenom ovog pristupa dobija se geometrija jednoslojne ljuske promenljive debljine ili geometrija dvoslojnih međusobno povezanih tanjih i lakših ljuski. U radu je prikazan metod dinamičke relaksacije primenom softverskog paketa Rhinoceros 3D. Implementacija ovakvog metoda u specifičnom softverskom paketu bi omogućila arhitektama, u ranoj fazi projektovanja, da definišu formu koja ima poboljšane performanse pod dejstvom seizmičke sile.

**Ključne reči:** dvoslojne ljuske; seizmički dizajn, parametarski dizajn, dinamička relaksacija

**PARAMETRIC ALGORITHM FOR FORM-FINDING OF DOUBLE-LAYERED  
SHELLS SUBJECTED TO SEISMIC LOADING**

**Resume:** When subjected to horizontal seismic forces, the geometry of the shells plays a key role in their behavior, primarily due to their light mass and high geometric rigidity. Previous research has shown that definition of the shape of shells is based on three-dimensional mesh models obtained through dynamic relaxation algorithms, taking into account the shell's own weight and the horizontal seismic force acting in at least two orthogonal directions. Applying this approach, the geometry of a single-layer shell with variable thickness or the geometry of two-layer interconnected thinner and lighter shells is obtained. This paper presents the method of dynamic relaxation using the Rhinoceros 3D software package. The implementation of such a method in the specific software package would allow architects, at an early stage of design, to define a form that has improved performance under the action of seismic force.

**Keywords:** double-layered shells; seismic design, parametric design, dynamic relaxation

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## 1. INTRODUCTION

When considering horizontal seismic forces, the geometry of shells plays a key role in their behavior, primarily due to their light mass and great geometric stiffness. Nevertheless, seismic loading is rarely taken into account in the initial design of shells, although it could significantly improve material efficiency and seismic performance. In recent research, methodologies have been developed that generate forms for shells designed to carry their own weight and seismic load through 3D models of suspended networks of cables obtained by implementing a dynamic relaxation method [1]. By applying this approach, the geometry of a single-layered shell with variable thickness or the geometry of two-layer interconnected thinner and lighter shells is defined.

The aim of this research is the implementation of the method in a software that allows great flexibility in the creation of 3D models and is used in the early stages of the design during the genesis of the very form of architecture. Rhinoceros3D [2], through its Grasshopper virtual programming environment, is used mainly for parametric design. In this paper, the application of the method in the Rhinoceros 3D software package is presented. Through implementation in the virtual programming environment Grasshopper and the programming language Python, an algorithm is built, which, for a given layout shape, defined boundary conditions and seismic force intensity, generates a double-layer shell. Dynamic relaxation is performed using Kangaroo [3], which is an integrated plugin in Grasshopper, after which the proposed algorithm from the obtained shells of different load cases defines the envelope of the double shell.

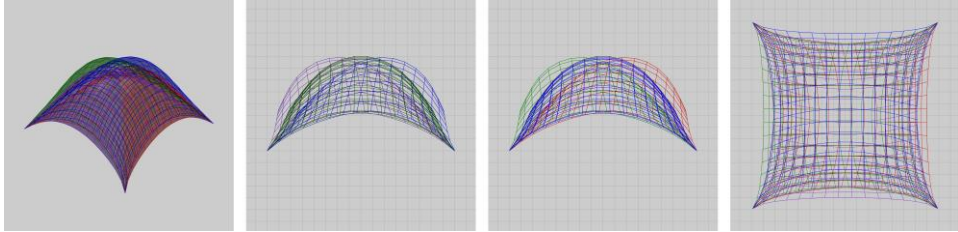
The algorithm is a visual algorithm developed through Grasshopper, based on the principle of components and connections between them. Grasshopper components are preprogrammed, ready-made segments of code that perform specific tasks. Such components connect with each other to build an algorithm that performs the desired task. However, not all necessary functions are available as ready-made components, certain specific functions must be written as classical code, through a programming language. This code is entered as a new component that builds on the visual algorithm.

Developing methods within this framework means that the form that this research examines in terms of its bearing characteristics, through the same 3D model, can be further considered in terms of various parameters that are of interest to the designer.

## 2. OBTAINING INDIVIDUAL SHELLS BY DYNAMIC RELAXATION METHOD (VISUAL ALGORITHM)

In order to obtain the envelope of a double shell, first the individual shells of different load cases are defined. In this research, 5 different load cases were taken into consideration: a load case representing gravity loading without any horizontal acceleration and 4 combinations of gravity and horizontal seismic acceleration in both orthogonal directions, in the positive and negative directions with an acceleration intensity of 0.45g.

The algorithm used by Kangaroo to perform the operation is a form of dynamic relaxation, a numerical method based on solving a set of nonlinear equations. Dynamic relaxation follows the movement of the structure over time at a given loading and just like the Verlet method [4], it is used to integrate Newton's second law over time [5].



*Figure 1 Overlapping of the shells obtained by modeling with different loading cases*

By combining all the forces acting on each point, the equilibrium is determined by the constant displacement of all points through several iterations until the forces are balanced and the movement stops, that is, until the structure stops in static equilibrium. This happens in a dynamic way so that the motion will oscillate around the equilibrium and damping is used to remove the energy and ensure convergence. In typical engineering applications of dynamic relaxation, the desired output is a static equilibrium configuration for given boundary conditions.

In this case study, a square base is taken that rests on pinned supports at its corners, which is divided into 10 x 10 mesh in Grasshopper. In this implementation, the shell surface is represented digitally by discretizing the surface into a network of linear elastic springs connected at nodes with free rotation. Gravity and earthquake accelerations ( $a$ ) are applied to each node, generating loads. The discretized model is given to the Kangaroo solver which models the shells by way of dynamic relaxation. The resulting model behaves like a cable net that stands in pure compression under a combined loading of gravity and horizontal acceleration, as it is the inverse of a net that hangs in pure tension under such loading.

The process of modeling the shell is entirely performed in the Grasshopper virtual environment and is an algorithm created through the visual programming language of the same name. The shells obtained in this way represent input information for the algorithm which generates the envelope of the double layered shell as output information. Considering that the specific functions needed to generate the envelope are not available in Grasshopper, a classic algorithm was programmed in the Iron Python programming language (version 2.7.3) [6]. Iron Python is integrated into Grasshopper and directly builds on its visual algorithms, thus enabling the formation of a continuous process.

## **2.1. DISCONTINUITY IN GEOMETRY**

Kangaroo can generate two lists as output in addition to the mesh: a list of points-nodes and a list of lines-springs connecting the points. The number of points and lines is identical to the number of nodes and springs that formed the original mesh of the base, which means that for the resulting shells a list of reference points-vertices is obtained that should be analyzed to define the envelope.

The initial approach to the analysis was to group the points into quadrants with respect to their  $x$  and  $y$  coordinates, i.e. creating a list of groups of points where if the  $x$  coordinate of a certain point belongs within certain limits and the  $y$  coordinate belongs within certain limits, then the point belongs to a specific group on the list. In a visual

sense, this represents an orthogonal grid of square fields projected in the horizontal XY plane, and all points, whose projections in the horizontal plane belong within the boundaries of one field, form a group. The resulting list of groups was analyzed by looking at all the points within the group and the algorithm singles out the point that has the highest Z coordinate and the point that has the lowest Z coordinate. The algorithm sorts the points defined in this way into two lists, a list of points with the largest Z coordinate, which is used to generate the upper layer of the shell, and a list of points with the smallest Z coordinate, which is used to generate the lower layer of the shell.

The set algorithm successfully selects the points, but it is dependent on the initial definition of the mesh, that is, a large number of nodes and springs needs to be defined as input information. Otherwise, if the number of defined nodes-points is not sufficient during their grouping, groups are created within the frames of which there are no reference points from each shell, which results in discontinuity of the geometry of the two-layered shell defined by the points. Different directions and directions of horizontal forces result in different displacement of vertices creating uneven distribution of reference points and formation of voids.

When considering certain groups of points, it is possible that no reference point from the shell that has the largest Z-coordinate in that segment exists, which leads the algorithm to choose a point that is not the true maximum for that segment, resulting in an error in the definition of the envelope ( Fig. 2). The error correction is removed when a high-resolution mesh, i.e. a mesh with a large number of nodes, is specified during the initial calculations in Kangaroo.

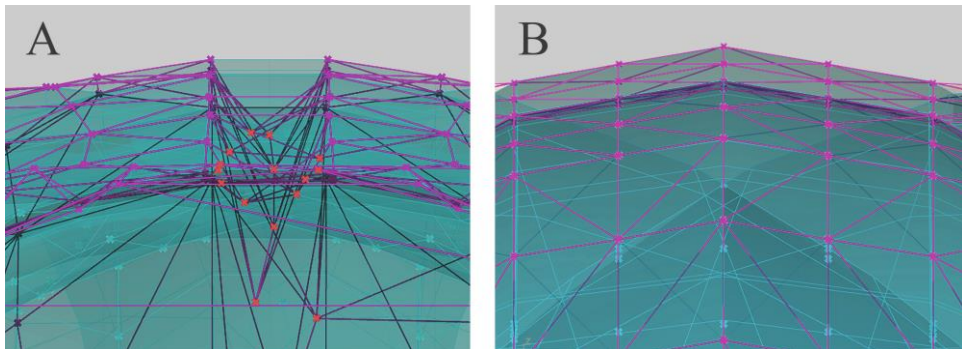


Figure 2 Error in network definition: A) discontinuity in shell geometry; B) the result after the correction of the input data

Such an approach cannot precisely determine the required number of nodes during the initial definition of the network, and the required result is obtained by trial and error. Also, providing a high resolution mesh as input to the Kangaroo algorithm significantly slows down the solver and negates its greatest advantage, providing a precise approximation of the shape using a small number of reference points.

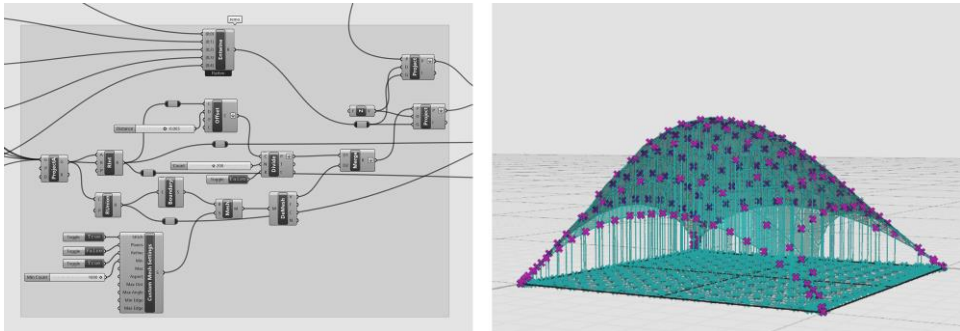
## 2.2. INPUT DATA CORRECTION

In order to overcome the problem with the discontinuity of the geometry from the initial approach, the input information- the points were considered, since it is necessary to

confirm that a representative sample of reference points is defined for each considered segment.

When considering this problem, it is important to emphasize that the Kangaroo solver as a result, generate a mesh and not just as a list of reference points. Grasshopper defines meshes using a data structure: vertex, mesh point - face, polygon. This structure is simply a list of points that are grouped into polygons (triangles or quadrilaterals) that form one continuous surface. Initially the algorithm works only with the vertices of the network, using them directly as reference points. But a surface (mesh) is also obtained, not just a list of vertices, which offers the possibility to define an unlimited number of points belonging to the surface.

A built-in Grasshopper function is used to determine reference points from the shells: *Project Point*, which allows any given point to be projected onto a given geometry in the direction of a given vector. In the specific case, this means that if a series of points are set in the horizontal plane, they can be projected onto the shells in the direction of the Z axis (Fig. 3). This approach offers two advantages. Namely, the projected points are fixed in terms of their x and y coordinates for each of the individual shells, thus obtaining reference points that have identical x and y coordinates, which allows overcoming the problem of creating voids, obtaining reference points from all shells which exist for the given coordinates. In addition, projecting a point on a given surface is a process that the software works with much faster and easier, compared to the Kangaroo solver, which leads to a faster result and allows obtaining a much larger list of reference points, that is, a much more precise definition of the envelope.



*Figure 3 Defining new entry points through the projection of points from the XY plane onto the shells in the direction of the Z - axis*

When defining the series of points, it is important to define the boundary in which the points will be set, in order to obtain reference points, so that the envelope can cover all the shells with certainty. As the boundary of the reference points for obtaining the upper layer of the shell we define the part of the XY plane in which at least one of the shells exists, while as the boundary for the lower layer of the shell we define the part of the plane in which all the considered shells exist. This is necessary because in certain segments there is only one of the shells and in such a case it represents a part of the upper layer of the shell, and since there are no other reference points it would be defended as both the highest and the lowest point. Boundaries are formed by taking the projections of each of the shells in the XY plane and defining their union and their intersection. The

points are given as vertices of a grid defined by the union of curves of all projections of the shells in the horizontal plane. This list of points is supplemented by the points of the curve which defines the difference of all projections in the horizontal plane.

### 3. PYTHON COMPONENT FOR SELECTION OF HIGHEST AND LOWEST POINTS (CLASSICAL ALGORITHM)

The functions of the algorithm described so far are defined through a visual language, without classical writing of code, because so far the necessary operations can be done by already existing Grasshopper components. However, the grouping of points according to their xy coordinates and the selection of the local highest and lowest point according to the z coordinate are not available as a ready-made component in the virtual environment and must be scripted as a new native component. Grasshopper supports the use of several programming languages: Python, C# and VB.Net. For the purposes of this paper, it has been decided that the code will be written in the Python programming language.

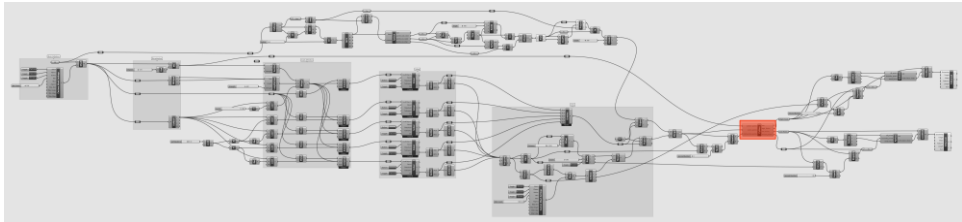


Figure 4 The visual algorithm built from available components (the new component programmed through Python is highlighted in red)

In the new Python component, three lists of points are defined as input data, a list of points obtained by projection of the points within the union of the projections (union\_points); a list of points that belong to the intersection of the projections (intersection\_points) and a list of points that are stationary during the simulation – pinned supports (anchor\_points). Three lists of points are obtained as output data, which define the upper and lower layers of the shell, i.e. the upper and lower limits of the envelope, and the stationary points - the supported - are separated again as separate ones.

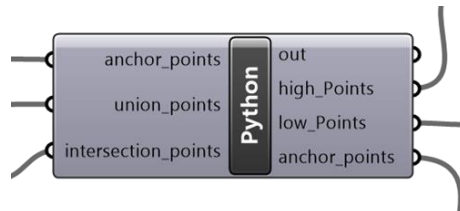


Figure 5 The component scripted in Python, which performs the selection of the highest and lowest points

The first step is to purge the list of points that we enter as input data from Grasshopper. This entails deleting any empty elements that might accidentally be on the list as result of the process in Grasshopper. For this purpose, the function filter is called which is available from the Python core library, which requires two arguments: a criteria to list and a list to be checked.

```
union_temp = filter(None, union_points)
intersection_temp = filter(None, intersection_points)
```

The first function we define helps us calculate the distance between the projections of two points on the XY plane using their x and y coordinates. Since the distance calculation will be used multiple times in the algorithm, it is best to define it as a function that will be simply called later.

```
def distance_xy_points(pt1, pt2):
    d = math.sqrt((pt1[0]-pt2[0])**2 + (pt1[1]-pt2[1])**2)
    return d
```

The function defined in this way is used to identify the clusters of points that are created around the supports (the points that were defined as stationary when calculating the shell through the Kangaroo solver). Kangaroo cannot define an ideal stationary bearing/point, therefore, in different load cases, it comes to defining different positions of the bearing that are at a minimum distance between each other. Although this deviation in reality is negligible, it can lead to errors in the operation of the algorithm, and therefore it is best to eliminate these clusters and replace them with the original bearing points, the ones assigned to Kangaroo. To identify, the function for calculating the distance between points is used, that is, the points that are very close to the original bearing points are extracted from the list of points, and they are deleted.

```
cluster_union = []
for point in union_temp:
    for anchor in anchor_points:
        if distance_xy_points(point, anchor) < 0.1:
            cluster_union.append(point)
list_union = []
for point in union_temp:
    if point not in cluster_union:
        list_union.append(point)
cluster_intersection = []
for point in intersection_temp:
    for anchor in anchor_points:
        if distance_xy_points(point, anchor) < 0.1:
            cluster_intersection.append(point)
list_intersection = []
for point in intersection_temp:
    if point not in cluster_intersection:
        list_intersection.append(point)
```

After deleting the clusters on the list of points, the original points of the supports (anchor\_points) which were taken as input information on a separate list from Grasshopper are returned.

```
list_intersection.extend(anchor_points)
list_union.extend(anchor_points)
```

The next step is to group the points according to their xy coordinates. The same function is used to calculate the distance between the projections of two points. The new definition of the input points results in which points have the same, or approximately the same, x and y coordinates. Namely, the groups of points are now not formed from points whose coordinates belong to a certain domain, but are grouped together if they have the same, or approximately the same x and y coordinates, whereby approximately the same coordinates mean that there is a certain degree of tolerance, in order to take into account the possible inaccuracy when the algorithm considers rational numbers, due to the rounding of decimals.

```
list_of_groups_union = []
list_of_groups_intersection = []
tracker_union = []
for point_1 in list_union:
    if point_1 not in tracker_union:
        group_union=[]
        for point_2 in list_union:
            if distance_xy_points(point_1, point_2) < 0.01:
                group_union.append(point_2)
                tracker_union.append(point_2)
        list_of_groups_union.append(group_union)
tracker_intersection = []
for point_1 in list_intersection:
    if point_1 not in tracker_intersection:
        group_intersection=[]
        for point_2 in list_intersection:
            if distance_xy_points(point_1, point_2) < 0.01:
                group_intersection.append(point_2)
                tracker_intersection.append(point_2)
        list_of_groups_intersection.append(group_intersection)
```

Points grouped like this are considered in terms of their Z coordinates, their height. Two points are selected from each of the previously defined groups, one with the highest Z coordinate, the other with the lowest. The selected points are grouped into two new lists, a list of points with the highest Z coordinates (high\_Points) and a list of points with the lowest Z coordinates (low\_Points).

```
high_Points = []
low_Points = []
high_point = list_of_groups_union[0][0]
low_point = list_of_groups_intersection[0][0]
for i in range(len(list_of_groups_union)):
    max_Z = float('-inf')
    for point_x in list_of_groups_union[i]:
```

```

        current_Z = point_x[2]
        current_point = point_x
        if current_Z > max_Z:
            max_Z = current_Z
            high_point = current_point
    high_Points.append(high_point)
    for i in range(len(list_of_groups_intersection)):
        min_Z = float('inf')
        for point_x in list_of_groups_intersection[i]:
            current_Z = point_x[2]
            current_point = point_x
            if current_Z < min_Z:
                min_Z = current_Z
                low_point = current_point
    low_Points.append(low_point)

```

These two lists represent output information from the Python component which further defines new grids representing the upper and lower bounds of the envelope with the help of available components from Grasshopper.

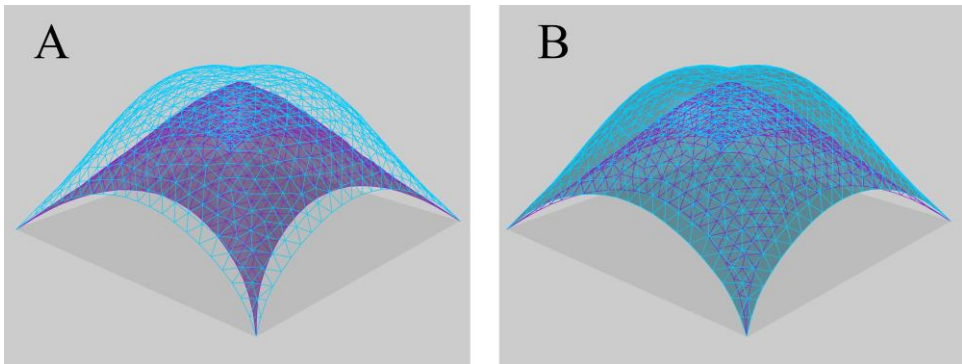


Figure 6 Final results of the selection of the points: A) Lower limit; B) Upper limit

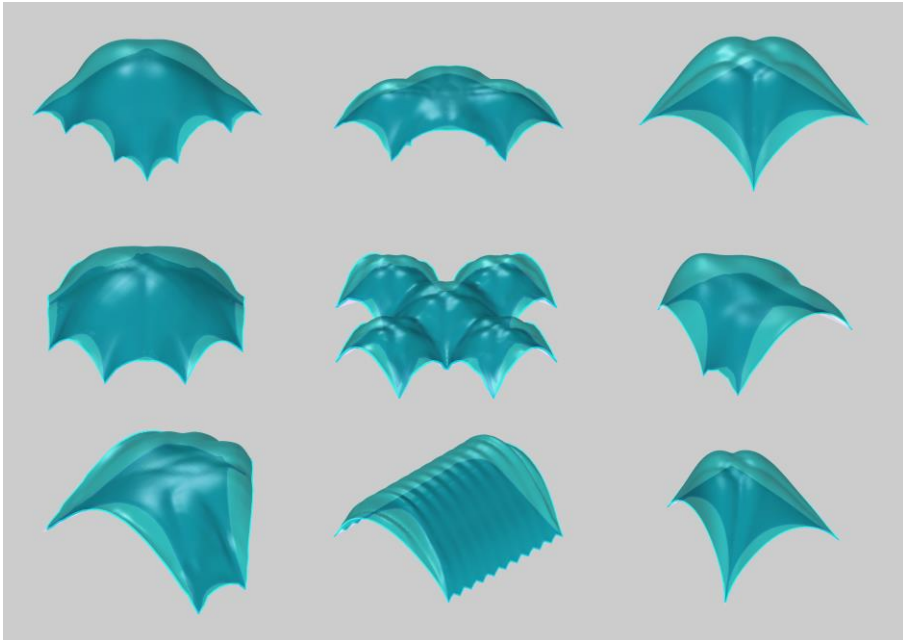
#### 4. CONCLUSION

The biggest benefit of implementing dynamic relaxation, as a method of creating the form, in the early stages of the design can significantly improve the final result of the form in terms of load-bearing characteristics. Such algorithms are primarily intended for architects and planners and reduce the time required for the development of the project, enabling an efficient process through which a variety of possible solutions of the form are quickly and simply considered, which always take into account the given form of the base, the defined boundaries conditions and intensity of seismic force. The added value of the forms obtained in this way, in contrast to the arbitrarily designed ones, represents a much better basis for further development and constructive analysis, which means fewer changes in the design process and better control from the beginning.

Defining the envelope is a function that is built into different software packages, but for the set purposes it is necessary to implement the method in the appropriate

software, so its entry into Rhinoceros3D and Grasshopper makes it available as a tool for projecting the shape even when defining the very concept for the project, and by applying the specific software, analyzes from the aspect of aseismic design are possible. In addition, working in parametric software allows the generated forms to be immediately considered from other aspects in relation to the program requirements, the environment, the lighting, so that the optimal form can simply be adopted.

Future research should be aimed at refining the proposed algorithm and further testing it on different base shapes, geometric irregularities in the base, and defining the support points in terms of how they affect the shape.



*Figure 7 Top and bottom layer of shells obtained using the presented algorithm*

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