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CEILING CONSTRUCTION WITH ACOUSTIC PANELS FOR SOUND DIFFUSION

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Summary: *The development of technology, from the end of the 20th and the beginning of the 21st century, led to the development of software design. Software analysis of space acoustics enables the design of theater and concert facilities of high acoustic performance. In contrast to the newly built facilities, of high quality acoustics, there are many theater and concert facilities built in the past that are characterized by lower quality acoustics. On this occasion, the aim of this paper will be to propose a solution for a constructive assembly for sound diffusion that would improve the acoustic characteristics of existing concert and theater facilities. The design of the, organic form, panel was done by software using the principles of the Schroeder sound diffuser. In addition to the design of the acoustic panel, the aim of this paper is to design a prefabricated structural assembly in which it is possible to install such panels. The proposed solution of the structural assembly, which would carry acoustic panels, is envisaged to consist of: membrane construction in the form of formwork, conoid concrete shell and styrofoam panels. Software analysis of the acoustics of the theater space with and without built-in acoustic panels resulted that the installation of the same contribute to improving the quality of space acoustics. The design of the previously mentioned ceiling element would enable quick and easy installation of the same in the existing theater and concert facilities, which would contribute to the acoustics of the space.*

Keywords: *Parametric design; organic forms; acoustics; sound diffusion; Schroeder's diffuser*

1. INTRODUCTION

We are witnessing the fact that the beginning of the 21st century has brought with it the accelerated development of technology. The development of software design, among other things, enabled the improvement of the acoustics of performance halls. Sound quality is an important characteristic of the space, especially when it comes to theater and concert facilities. The acoustic characteristics of the space can significantly affect the performance experience itself. The importance of acoustics is also indicated by the fact that today in process of designing performance halls are hired engineers, responsible only for a space acoustics. However, the problem arises from aspiration to improve the acoustic characteristics of construction facilities built in the past.

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In order to improve the acoustics of the space, the first acoustic panels were created. With the advent of the first Schroeder diffuser, in 1975, the design of acoustic panels became a topical issue. With its geometry, dynamic arrangement of segments, the panel would reduce direct reflection, as well cause the diffusion of sound waves that bounce off its surface [1-5]. Sound diffusion enables balanced distribution of sound in the room and eliminates the possibility of creating an echo. At the beginning of the 21st century and with the development of software design, this topic gained a new dimension due to the tendency to shape the geometry of panels with organic forms, so that they contribute to both acoustics and aesthetics of space [6-8].

In addition to the design of the panel, it is necessary to analyze the installation of the same. Modern tendencies in the design process based primarily on material savings have led to the creation of a large number of innovations in the field of modern structural systems. One of them is the use of a membrane construction as a formwork for a thin-layer concrete shell. By applying the membrane construction, the material for the formwork is saved [10-12].

The aim of this paper is to propose the design of a structural assembly of ceiling acoustic panels for sound diffusion. The geometric design of the panels will be based on the geometry of the panels used in the interior of the Elbphilharmonie building in Hamburg, using the principle of the Schroeder diffuser [6]. The panels would be part of the structural assembly in the form of a droped ceiling. Comparative analysis of the acoustics of the theater space, with and without acoustic panels, obtained by software, leads to the results that the installation of ceiling elements would contribute to the acoustics of the room, due to diffusion and a significant reduction in sound reflection.

2. ACOUSTIC PANEL DESIGN

In this chapter, the focus is on designing the sound diffusion panel itself. Advances in software design have enabled the creation of panels of organic forms, which, in addition to improving acoustics, would also contribute to improving the aesthetic values of the interior in which it will be located. Parametric design has provided a multitude of possibilities for panel design in terms of geometry. Extensive possibilities of parametric design with software analysis of acoustics have led to the creation of many panel solutions for improving the acoustics of space. Within this paper, one of the possibilities of designing sound diffusion panels will be proposed.

Before the design of the panel, the dimension of the panel was chosen, which can be arbitrary, and in order to demonstrate the methods in this paper, it is assumed that the panel is rectangular with dimensions of 100x50cm. An analysis of the principle of operation of the Schroeder diffuser showed that the panel consists of smaller segments of different depths. The Schroeder sound diffuser is designed to contain a dynamic arrangement of recesses, with the sound wave being reflected from the recess walls on the panel itself (Figure 1.2). This would allow the sound to spread evenly in multiple directions. Such a principle reduced the direct reflection of sound (Figure 1.3), from smooth surfaces, thus reducing or completely preventing the creation of echoes in space [1-3].

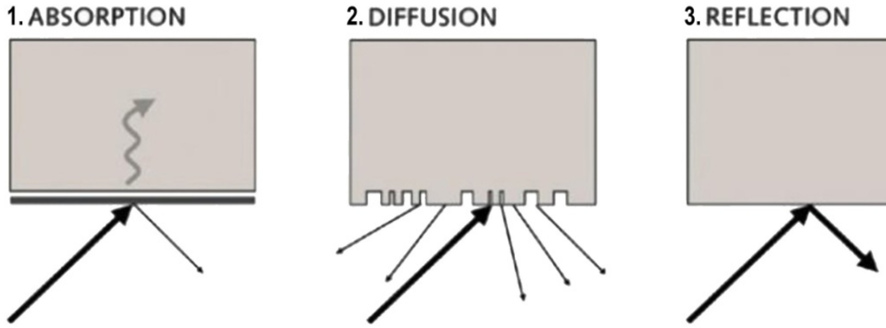

Figure 1. Occurrences in sound propagation (Koren, 2009. pg.238.)

By applying the 2D-SD principle, ie Schoeder's diffuser with division of segments in two directions, an adequate division of the panel into segments was determined. The 2D-SD method is based on dividing the panel into N = 7 segments, which implies a network of seven segments in the X and Y directions. This division leads to a square panel of 49 segments. However, as we previously selected the rectangular shape of the panel, the Mirror repetition approach was applied using the Mirror method. This resulted in a 2D panel measuring 50x100cm divided into 98 segments [4]. The panel thickness was obtained on the basis of a calculation in which the panel thickness (D) for adequate sound diffusion or absorption comes from the minimum wavelength (λ_0) of sound waves. First of all, it is necessary to determine the minimum wavelength (λ_0) based on the assumed sound frequency at the source (f_0) and the speed of sound propagation (c) [4]. In this case, the sound waves spread through the air, so the speed of sound (c) will be 343m/s, while for the minimum frequency of sound (f_0) we will take 2450Hz. It follows (1):

$$D = \frac{\lambda o}{2};\ \ c = 343\frac{m}{s};\ \ fo = 2450Hz;\ \ \lambda o = \frac{c}{fo} \ \Rightarrow$$
$$\Rightarrow\ \lambda o = \frac{343\frac{m}{s}}{2450Hz} \ \Rightarrow\ \lambda o = 0.14m \ \Rightarrow \qquad (1)$$
$$\Rightarrow\ D = \frac{0.14m}{2} \ \Rightarrow\ D = 0.07m$$

This gives a panel thickness (D) of 7cm. The calculation also shows that with this depth of the segments, the possibility of diffusion of its sound remains incomplete and that there are possibilities for improvement in future works.

After the adopted panel thickness, it is necessary to make a segment diagram based on the 2D-SD Schroeder's diffuser principle [4]. The depths of the segment (Sn) are obtained in relation to the thickness of the panel (D), so that *S=D*n*, where (n) represents a number from 1 to 6. (Figure 2) was made in relation to the depth of the segments, which is 0-6cm [4].

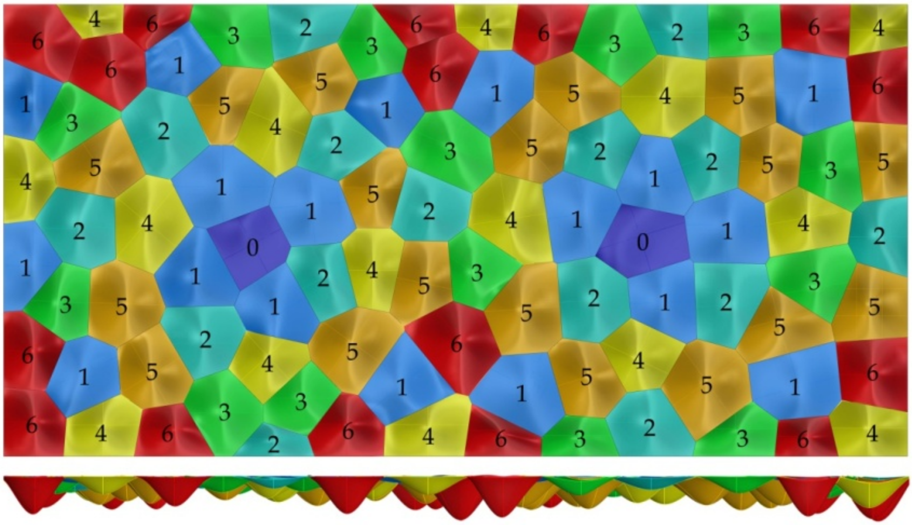

Figure 2. Schema of the layout and depth of the segments using the principle of the Schroeder's diffuser showing the depth of the segments in the layout

The geometric design of the panels was done with Rhino software using the Grasshopper plug-in. The pattern of layout and design of segments is based on a random division of a two-dimensional surface, measuring 50x100cm, with the help of generating Voronoi segments. The software enables random scrolling in order to control the degree of randomness of the layout and the size of the segments. The shaping of the Verona segment was performed with the aim of obtaining a dynamic geometric shape. When using the Voronoi pattern, a division into 98 segments is given with a layout that would strive to create 7 columns and 14 rows of two-dimensional segments. The size of the segments varies, the longest diagonals of the segments range from 8 to 12 cm. Surfaces were created from individual obtained 2D segments, which were then used to shape 3D segments by applying the NURBS (Non-uniform rational basis spline) modeling method. By moving the points, different 3D surfaces of a given depth are formed according to the layout scheme of the segments (Figure 2) [7].
After shaping the three-dimensional segments, it is necessary to connect them to form a surface (Polysurface) composed of these segments. The materialization of the acoustic panel is provided from gypsum-based materials. Materialization can be reported in two ways. The first method would involve shaping gypsum fiber panels using a CNC machine. Due to the appearance of different degrees of complexity of the edge geometry, it is recommended to use a 5-axis CNC machine in the production process. In this way, the CNC machine would remove excess material by creating indentations obtained by the parametric model [6,7]. Another way would be to make a mold, also by software, based on the obtained panel geometry. As the concept envisages the design of one type of panel that is repeated, making a mold is more convenient because it would save energy and material in relation to the production of a CNC machine. The mold can be obtained from wooden material shaped using a CNC machine. By using a wave-shaped mold, the gypsum material would be poured into it. Rapid hardening of the gypsum material would enable fast serial production of the panel, which is the goal of this design of the proposed acoustic

panel. In this way, a 3D gypsum panel with fibers would be created, the thickness of which would vary, depending on the recess of the segment, from 1 to 7 cm (Figure 3) [4].
In contrast to the geometric similarity, there are a number of differences between the panels presented in this work and the panels used in the interior design of the Elbphilharmonie building in Hamburg. First of all, the difference is reflected in the concept of application.
The acoustic panels used in the interior of the Elbphilharmonie building were obtained based on the analysis of the acoustics of the hall in which they were later installed. Such an approach enabled high-quality acoustics of the space. Also, such an approach involved the design of 10,000 different acoustic panels that cannot be used uniformly for other objects of similar purpose. In contrast, the panel presented in this paper, formed by the principle of 2D Schroeder's diffuser, enables serial production of the same but with lower acoustic quality compared to the previously mentioned acoustic panel. Serial production would enable the installation of panels in various buildings created in the past, where it is necessary to improve the acoustic characteristics [6,7].

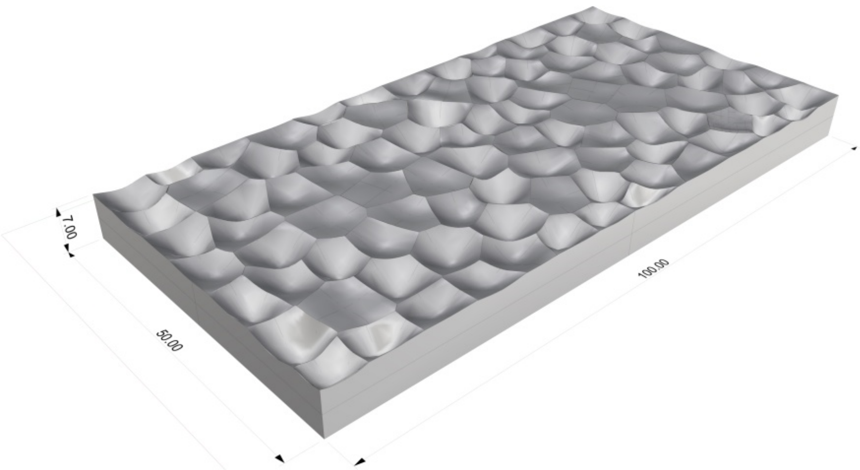

Figure 3. 3D view of the acoustic panel for sound diffusion

3. CONSTRUCTIVE ASSEMBLY

The structural assembly is a proposal for a solution of a structure that could support the acoustic panels described in the previous chapter. The role of the structural assembly is also reflected in the possibility of prefabrication, which would enable the delivery of finished structural elements and their installation in buildings. Prefabrication of the structural element would reduce the time required for the renovation of the building itself and it would reduce the time of construction works in the building itself. Installation of structural elements is provided in the form of a droped ceiling with steel cables. By regulating the lengths of the cables, it is possible to form different angles for placing the structural elements, depending on the needs of the space itself. The constructive assembly itself is designed to consist of: membrane (tensile construction), concrete shell, styrodur panels and acoustic panels for sound diffusion (Figures 4). The shape of the structural assembly would be a conoid with a rectangular base, measuring 250x100cm [9]. The conoidal shape of the structure was chosen because such a shaped shell could accept more loads in relation to the plane of the same thickness and material, and its shape requires less spent material for filling from EPS foam, in relation to surfaces such as domes, cylindrical shells…

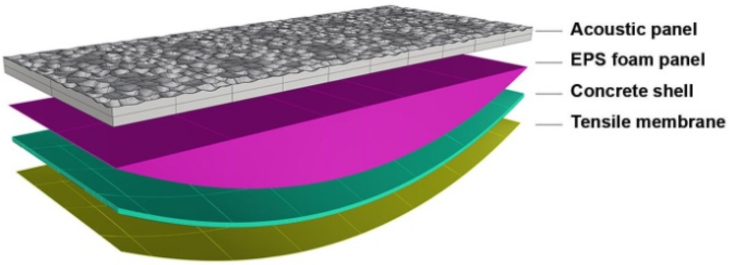

Figure 4. 3D view of the structural assembly

The process of building a structural assembly would begin with the formation of a membrane of textile material. Laying of the membrane by tensioning for a rigid frame construction should be performed so that after the installation of the membrane it acquires a conoid shape. In this case, the installed membrane will represent the formwork for the construction of the concrete shell. For the formwork, it is necessary to choose a textile material with sewn folds that would play a role in retaining the liquid material based on cement and water. The reason for installing textile membrane formwork is reflected in the lower cost of materials as well as the significantly shorter installation process, compared to traditional types of formwork. The irrational consumption of formwork materials is also indicated by the fact that the production of formwork, for double-curved surfaces, mainly made of wood or foam materials, can amount to up to 75% of the total construction cost of the structure [10].
After installing the formwork in the form of a membrane, it is necessary to start building a thin-layer concrete shell. In this case, the concrete shell is the main supporting structural element. The shaping of the concrete shell is performed in the form of applying three layers of material on a previously made formwork from a tightened membrane. A layer of cement paste is applied to the taut textile membrane first, then a layer of mortar and then concrete. Applying the first layer in the form of cement paste has the role of stiffening the textile membrane. In this way, a light construction of satisfactory rigidity is created, which would enable the avoidance of deformations due to the point load that occurs in the process of concrete installation. Only the drying of the cement paste is a process because it takes several days to achieve the desired strength of the material. After achieving satisfactory rigidity of the cement paste, the construction is ready for the application of the second layer, the application of a layer of mortar with reinforcement. The mortar is applied with a pressure gun, which enables even spraying on the substrate in a thin layer. Reinforcement of the construction in the form of a network of carbon fibers with epoxy coating is manually placed on the still fresh mortar. The role of reinforcement in the form of carbon fibers is to increase the resistance of the mortar to the formation of cracks that could occur

due to the load that will occur due to the application of a layer of concrete. After the mortar layer has hardened, concrete is applied, which is the last step in creating a concrete shell [11-13]. Fresh concrete mass is applied to the previously formed construction in a layer of 2-3cm, depending on the static calculation, which is not considered in this paper. The installation of anchors in the fresh concrete mass would enable the hanging of the construction of cables for the existing ceiling construction of concert and theater halls. By hardening the concrete, the thin-walled concrete shell would get its final shape [9,11-13]. Expanded polystyrene foam panels are then placed on the formed concrete shell. The shape of the panel was obtained from the geometric analysis of the concrete shell model. The process of shaping EPS panels would be done by precisely removing excess material with the help of an industrial robot using "hot-wire" technology. With their design, the elements made of expanded polystyrene have the role of absorbing part of the sound and filling the concrete shell, which creates a flat surface for the final installation of acoustic panels [14].
On the obtained flat surface measuring 250x100cm, it is necessary to place five acoustic panels for sound diffusion, analyzed in the previous chapter. In that way, a ready-made structural assembly for sound diffusion would be obtained, which is ready for installation in the form of a droped ceiling. By analyzing the process of constructing a structural assembly, we come to the conclusion that it is possible to perform prefabrication as well as serial production of the same.

4. ACOUSTIC ANALYSIS

Within this chapter, the results of software analysis of space acoustics without and with built-in structural elements will be presented. In order to test, a model of the theater space was created for about 300 spectators with a balcony. The depth of the auditorium (without stage) is 1550cm. The clear height of the experimental theater is h=770cm. Acoustics testing was performed by comparative analysis of acoustics of two experimental models by software Ecotect.
The results shown in Figures 5.1 and 5.2 were obtained by analyzing the echo estimation in the experimental model of theater with and without acoustic panels. The graph present the sound response time (in *ms*) based on the volume (in *dB*) and different frequencies (in *Hz*). By displaying the graphs, we can see that the response time of the sound, for the same volume (-24dB), of the frequency 2000Hz decreased from 1470ms (Figure 5.1) to 920ms (Figure 5.2). The installation of acoustic panels achieved an echo reduction of approximately 37.5%. By displaying the sound frequency curves of 2000Hz and 16000Hz, we see that the difference in sound response (volume -24dB) in the space with panels is less than 40ms (Figure 5.2), while in the space without panels it is greater than 750ms (Figure 5.1). A small difference in the response time of sound frequencies higher than 2000Hz was obtained by sound diffusion. In contrast, we can see equal response curves of low frequency sound, frequency 63Hz, which shows that there is room to improve the panels in order to better diffuse low-frequency sound.

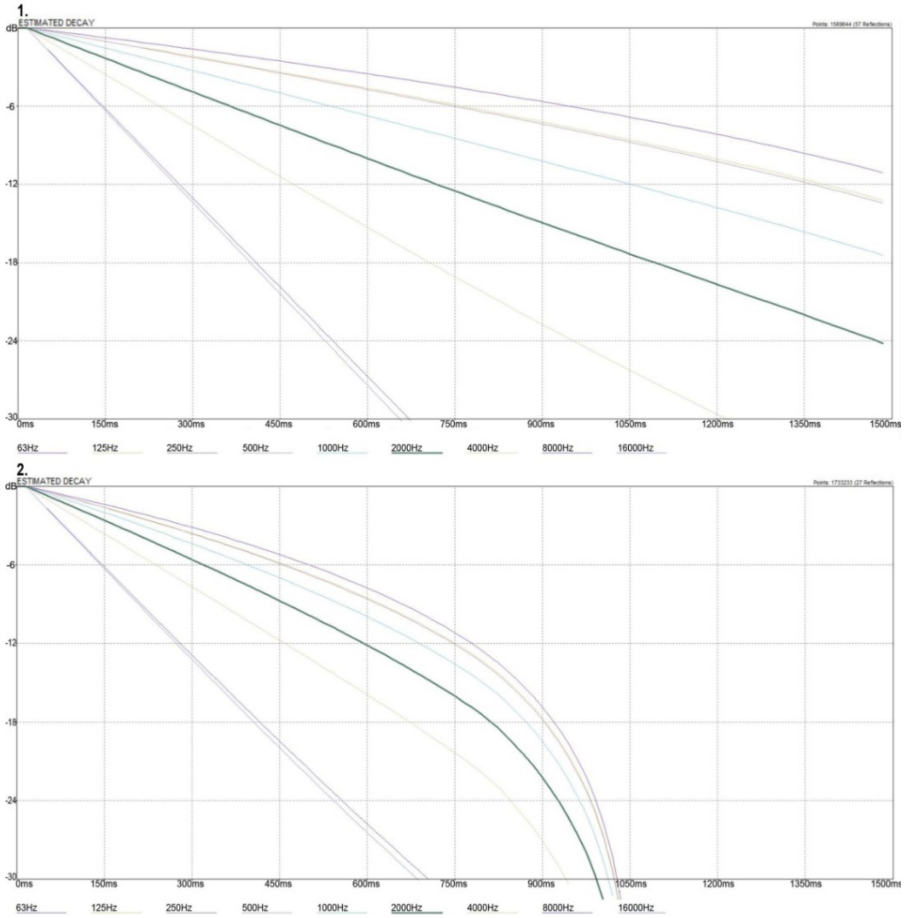

Figure 5. Graph of echo estimation of experimental theater model without(above) and with acoustic panels for sound diffusion(under)

5. CONCLUSION

In this paper, a solution proposal for the structural assembly of a ceiling acoustic panel for sound diffusion is presented. The design of the structural assembly, measuring 250x100cm, would enable its installation in already built theater and concert facilities, which would contribute to the acoustic characteristics of the space. Prefabrication of the structural element and installation of the same in the form of a droped ceiling would enable the reduction of construction works in the building itself. The constructive assembly is designed to consist of: membrane (tensile construction), concrete shell, styrodur panels and acoustic panels for sound diffusion. Membrane construction would have the role of formwork for the construction of a thin-layered concrete shell, which would also be the main supporting structural element. The installation of anchors for hanging steel cables is planned in the fresh concrete mass, through which the structural element would be attached to the existing construction of the building. The role of styrodur foam would be in leveling the surface to allow the installation of acoustic panels.

The last part of the structural assembly is the installation of five acoustic panels measuring 100x50x7cm. The acoustic panel is designed using the principles of a 2D Schroeder sound diffuser. The 2D panel is divided into 98 Voronoi segments. The depth of the 3D segments was obtained by the calculation used to shape the 2D Schroeder diffuser. The acoustic panel of organic form is defined by a parametric path in the Rhino software using the Grasshopper plug-in.

The analysis of the acoustics of the space leads to the results that the installation of ceiling structural elements would contribute to the improvement of the acoustics of the space. Installing acoustic panels would lead to the diffusion of sound in the room, which would reduce the percentage of reflected sound waves that create echo and masking sound. Despite the installation of acoustic panels, the analysis of acoustics, it was determined that there is still some percent of echo in space. Although there is significantly less echo generation, this data tells us that there are possibilities to improve the characteristics of the acoustic panel.

REFERENCES

[1] Schroeder, M.R, Diffuse Sound Reflection by Maximum-Length Sequences, The Journal of the Acoustical Societyof America 57, 149, 1975.
[2] Hargreaves, J.A, Cox, T.J, A transient boundary element method model of Schroeder diffuser scattering using well mouth impedance, The Journal of the Acoustical Societyof America 124, 2942, 2008.
[3] Cox, T.J, The optimization of profiled diffusers, The Journal of the Acoustical Societyof America 97, 2928, 1995.
[4] Zhu, Y, Fan, X, Liang, B, Cheng, J, Jing, Y, Ultrathin Acoustic Metasurface-Based Schroeder Diffuser, Physical Review X, 7, 021034, 2017.
[5] Barron, M, Auditorium Acoustics and Architectural Design, Spon Press, Secon edition, London and New York, 2010.
[6] Koren, B, A Parametric, Sound-Diffusive Surface Pattern for the Symphonic Concert Hall of the Elbphilharmonie, Design Modelling Symposium 2009, Universität der Künste Berlin, p.237-248, 2009.
[7] Koren, B.S, Muller, T, Digital fabrication of non-standard sound-diffusing panels in the large hall of the Elbphilharmonie, Fabricate 2017, Institute for Computational Design and Construction, University of Stuttgart and The Bartlett School of Architecture, University College London, 2017.
[8] Yang, X, Adaptive Acoustic Origami, University of Melbourne, 2017.
[9] Radivojević, G, Kostić, D, Konstruktivni sistemi u arhitekturi, Građševinsko-arhitektonski fakultet u Nišu, Niš, 2011.
[10] Chudley, R, Greeno, R, Hurst, M, Toplis, S, Advanced Construction Technology, Construction Technology, 5th edition, Pearson, 2012.
[11] Popescu, M, Reiter, L, Liew, A, Van Mele, T, Flatt, R.J, Block, P, Building in concrete with an ultra-lightweight knitted stay-in-place formwork: Prototype of a concrete shell bridge, Structures, Vol.14, p.322-332, 2018.

[12] Popescu, M.A, KnitCrete: Stay-in-place knitted formworks for complex concrete structures, ETH Zurich, 2012.
[13] Popescu, M, Rippmann, M, Liew, A, Reiter, L, Flatt, R.J, Van Mele, T, Block, P, Structural design, digital fabrication and construction of the cable-net and knitted formwork of the KnitCandela concrete shell, Structures, 2020.
[14] Bajšanski, I, Stojaković, V, Tepavčević, B, Jovanović, M, Mitov, D, An Application of the Shark Skin Denticle Geometry for Windbreak Fence Design and Fabrication, Journal of Bionic Engineering 14, 2017.

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КОНСТРУКТИВНИ СКЛОП ПЛАФОНСКИХ АКУСТИЧНИХ ПАНЕЛА ЗА ДИФУЗИЈУ ЗВУКА

Резиме: *Развој технологије, са краја 20. и почетка 21. века, довео је до развоја софтверског пројектовања. Софтверском анализом акустике простора омогућено је пројектовање позоришних и концертних објеката високих акустичних перформанси. Насупрот новоизграђених објеката, високо квалитетне акустичности, много је позоришних и концертних објеката изграђених у прошлости који се одликују нижим квалитетом акустичности. Циљ овог рада је предлог решења конструктивног склопа за дифузију звука који би побољшао акустичне карактеристике постојећих концертних и позоришних објеката. Обликовање панела, органске форме, вршено је софтверским путем уз примену принципа Schroeder-овог дифузера звука. Осим дизајна акустичног панела, циљ овог рада јесте и обликовање префабрикованог конструктивног склопа у који је могуће уградити такве панеле. Предлог решења конструктивног склопа, који би носио акустичне панеле, предвиђен је тако да се састоји од: мембранске конструкције у виду оплате, коноидне бетонске љуске и стиродур панела. Софтверском анализом акустичности театарског простора са и без уграђених акустичних панела дошло се до резултата да би уградња истих допринела побољшању квалитета акустике простора. Обликовањем претходно наведеног плафонског елемента омогућила би се брза и лака уградња истих у постојеће позоришне и концертне објекте, што би допринело акустици простора.*

Кључне речи: *Параметарско пројектовање; органске форме; акустика; дифузија звука; Schroeder-ов дифузер.*