Research Article

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The use of shells in the architecture of the concert halls**

Abstract: This paper deals with the use of the shells in the architecture of concert halls through research on the historical development of the concert building's space. These elements are widely applied in civil engineering and architecture due to the good operational qualities, very rich spectrum of forms, the simplicity of production and its technical efficiency. The article considers two types of shells: conoid and truncated cone to choose the most optimal form for covering the concert hall.

Keywords: shells; historical development; concert halls; technical efficiency; conoid and truncated cone

1 Introduction

The development of the form of concert halls takes quite a long period in the history of architecture. A large study of shape changes and acoustics was conducted in the work of Beranek [1], Long [2], and Baroon [3].

Until the XX century, the concert hall was a simple classical building and the most common forms were shoebox, fan, or hourseshoe.

The process of form evolution is well shown in the article by Jablonska *et al.* [4].

The shoebox form became widespread in the concert hall architecture in the XIX century, when the four halls with good acoustic performance were built, such as Grosser Musikvereinssaal (1870), Neues Gewandhaus (1884), Concertgebouw (1888), and Symphony Hall Boston (1900).

The design of these buildings was very much in the tradition of European XIX century halls, with plaster decoration applied to walls and ceiling [5].

However, in the XX century, with the beginning of the construction of concert halls with the possibility of audio recording or radio broadcasting of events, the audience space is becoming more and more complicated. New wall and ceiling designs are being introduced as the architects of the modern movement sought to move away from the classical rules in composition: the presence of symmetry and axes, the predominance of columns and stucco. New findings in the concert hall design are shown in the article by Marshall [6].

All these changes led to the expansion of the concert space. A growth in cubature in the shoebox, fan, or horseshoe-shaped layouts posed a threat of an overly prolonged reverberation time as well as of an echo [4]. This was the beginning of a completely new solution for a concert space for an audience of more than 1,600 people. The evolution of architectural design is shown in the Figure 1.

The opening of the Berlin Philharmonic in 1963 gave rise to new expressive means of shaping and complex non-linear forms are increasingly used in the exterior and interior of a spectacular building. The acoustic design of the hall also reflected the significant development in architectural acoustics after the Second World War, especially in the aspects of diffusion and early reflections [7].

With the advent of the Berlin Philharmonic, the beauty of architectural forms began to be combined with acoustics in concert halls.

It should be noted that the XX century is the beginning of experimentation not only with the internal layout of the concert hall but also with its external appearance, which was then formed in the period of organic architecture [8].

Instead of the traditional representative static composition, the architect Hans Sharoun designed a complex modern space organized from oblique lines and completed in the form of a "tent". This interesting roof structure consists of the five cross arm trusses with varying height [9].

Nowadays the construction of concert buildings uses various forms of the past, taking into account the modern

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development of society and scientific and technical achievements. In the age of innovation, a strong and at the same time original architectural image has become necessary to transform a building into a central element of the urban environment. Modern architecture is constantly seeking new ways of expression, leading to complex architectural geometries [10]. And this gave rise to an extensive complex of architectural and structural solutions for such spatial structures as shells. The prospects and relevance of shells are presented in detail in the article of Korotich [11]. As well as an extended complex classification of shells is also presented by this author in the article [12].

The architecture of modern concert halls is dominated by spatial structures of various forms as it is shown in Figure 2.

The detailed presentation of different types of surfaces can be found in the encyclopedia of Krivoshapko and Ivanov [13]. An overview and classification of new surface forms are also presented in the article of Grinko [14].

Among the surfaces that are common in design, a good coating option for a concert hall is the linear surfaces, such as a conoid or a truncated cone. These shells are described in the article of Korotkiy [15]. They are widely used in the architecture of buildings for various purposes: from residential to public buildings. This type of shell structure can be built to what appears to be the ultimate in the lightness of construction, minimum reinforcing, and ease of moving forms [16].

The conoid shell was used in buildings such as the school at the Sagrada Familia Cathedral and the San Jordi Palace (Barcelona, Spain). The structural scheme of the Sagrada building contains a load-bearing beam, perpendicular to which the wooden rafters are laid, the ends of which are arranged in parts of a sinusoid, forming the shape of a conoid. In the Palace building, the conoid is used as a structural element on the edge sections of the roof.

Examples of using the cone include the Cathedral of Saint Sebastian (Rio de Janeiro, Brazil), the Library of the Delft Technical University (Delft, the Netherlands). St. Sebastian's Cathedral is shaped like a truncated cone with an outer diameter of 106 m and an inner diameter of 96 m. The roof of the Delft University of Technology library is an inclined plane with a 40 m high cone in the center as a symbol of technological progress and engineering, which includes four levels of study rooms connected by a spiral staircase. The examples of using two shells are given in Figure 3.

The authors conduct a detailed study of these two types of shells, demonstrate their strength characteristics, and make a comparative analysis in order to select the most optimal form for the project of the concert hall.

The study is conducted using the interconnection of two programs: ArchiCAD and SCAD to automate the transition from the architectural design of the building to the design model.

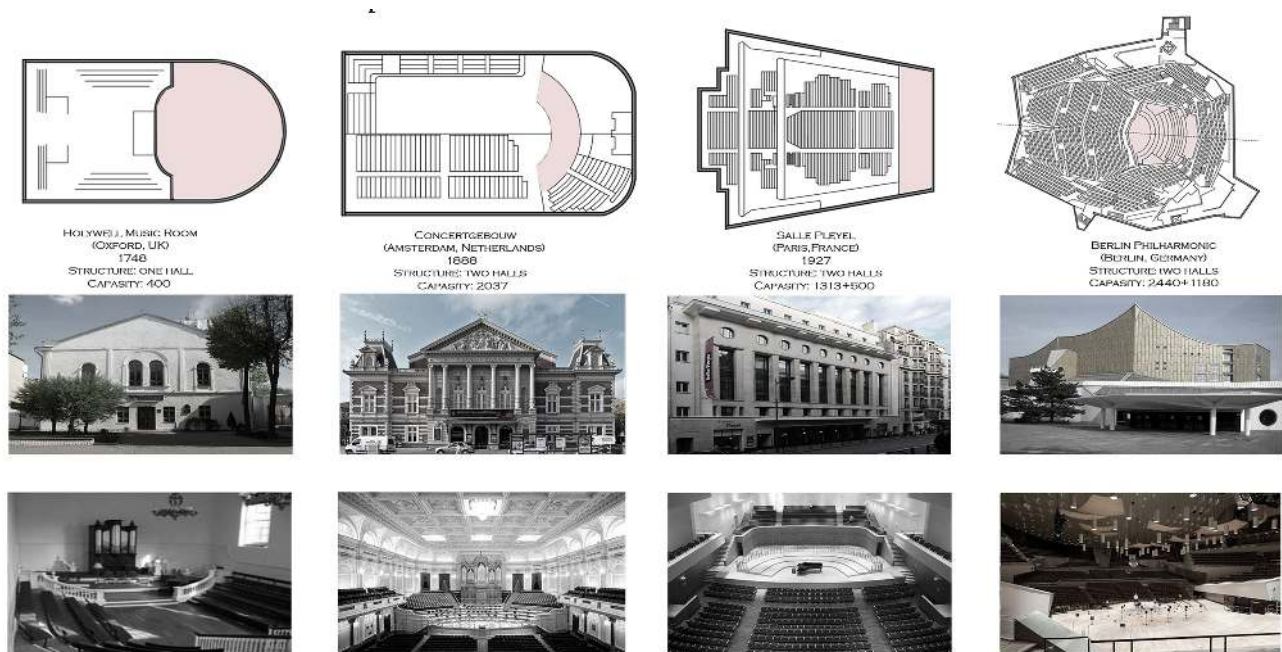The use of specialized software systems in architectural design allows to use existing architectural models of the

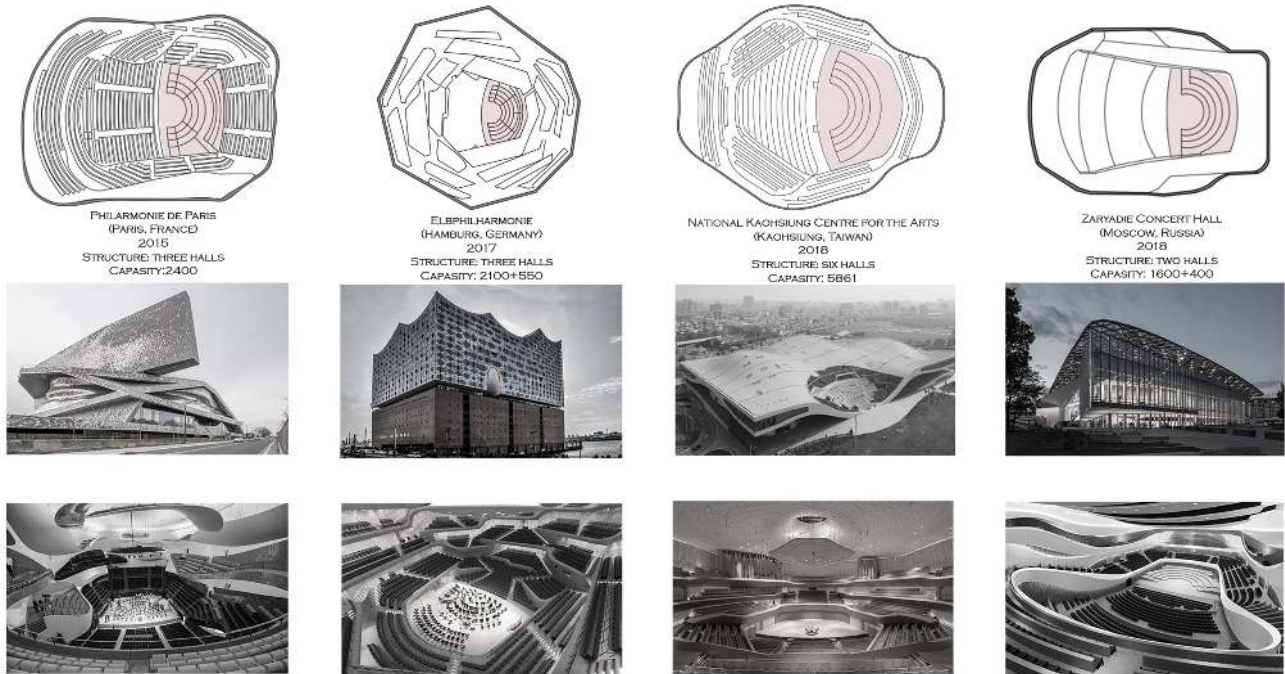**Figure 1:** The concert halls before the Berlin Philharmonic
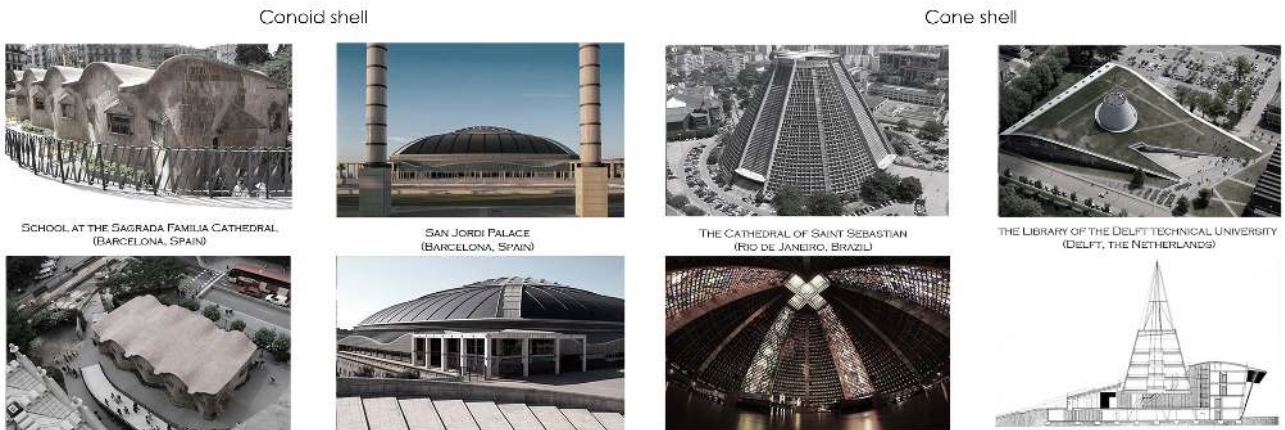
Figure 2: The modern concert halls

Figure 3: The using of conoid and cone shells in the buildings

object when building design schemes: access to architectural information is organized, and the design scheme is automatically built on its basis [17].

2 Main part

2.1 The description of two shells

The conoid shell belongs to linear surfaces of negative Gaussian curvature and is formed by the movement of a straight line (*l*) parallel to a fixed plane (*σ*) and intersecting two fixed lines (n, m) – the straight axis of the conoid (n) and the guide curve (m) (Figure 4a).

In this paper, we study a conoid with a directrix catenary, which is formed by the movement of a straight line that intersects two fixed lines – the fixed straight line, which is the axis of the conoid and the fixed director catenary itself, which is a curve (Figure 4b, 4c). This type of surface is given by the following equation:

$$z = \frac{x}{l}\left(a\,ch\frac{y}{a} - a - f \right) \qquad (1)$$

where: *a* is a radius of the directrix circle; *f* is the distance from the peak of the circle place in the plane *x = l* till the
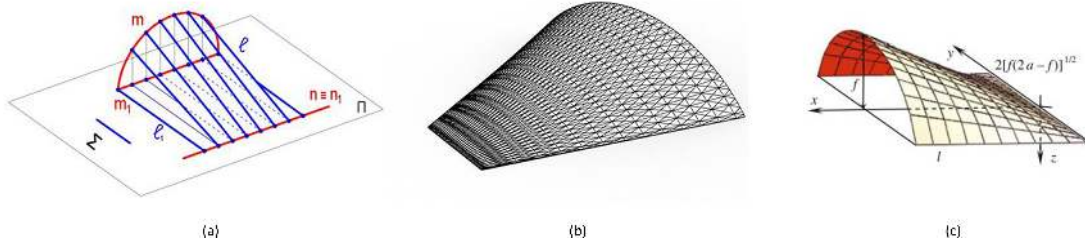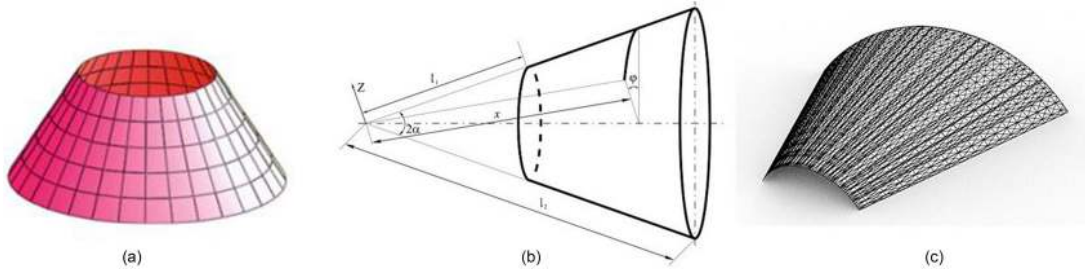
Figure 4: The conoid shell

Figure 5: The truncated cone shell

plane $z = 0$ (a rise); l is a distance between planes with directrix hyperbolas; ch is a hyperbolic cosine.

The conoid with a catenary covers a rectangular plan with dimensions equal to:

$$l \times 2aArch\left(1 + \frac{f}{a}\right)$$

where: Arch is an inverse hyperbolic cosine.

A conical surface is a surface formed by the movement of a straight line (generatrix) passing through a given point (vertex of a conical surface) and intersecting a given line (guide) [9]. The canonical equation of the surface:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 0 \qquad (2)$$

In this paper, we will consider a truncated cone shell (Figure 5a, 5b, 5c).

2.2 The comparative analysis of two shells

Two forms with defined dimensions were created in the ArchiCAD program (Figure 6a).

The length of two sides of the shells is 57 m and the span is 80 m. The area of a conoid is 3168.445 m^2 and of a cone is 3326.63 m^2.

Then the forms were exported to the SCAD program for further calculation. The design schemes of the two shells consist of plate elements with rigid fastening on three sides (Figure 6b). The outer radius of the conoid and cone has a free bearing as it is shown in the Figure 6b.

The shells are made of B25 concrete with a volume weight of 2.5 t/m^3. The thickness of the shells is taken 0.2 m.

Then a comparison is made for the following parameters:

1. Deformation (Z-axis);
2. normal stresses (Nx and Ny);
3. moments (Mx, My, Mxy).

To perform the calculation, three loads are applied to the shells: own weight (0.5 t/m), coating load (0.11 t/m), and snow load (0.35 t/m). The deformed scheme is shown in Figure 7(a) and Figure 8(a).

Also, the overall stability analysis is conducted for the two shells by a combination of three loads together. The stability coefficient is carried out in the range [0, 500.0], where 500.0 is an estimate of the upper limit of the search interval for the stability coefficient, which is set in the source data. If the stability factor is greater than the specified upper limit, it is not calculated. The coefficients of the stability of these shells were calculated and included in the interval. The coefficient of stability for the cone is 2.148, for the conoid-2.377. Forms of stability loss are presented in the Figures 7(b) and 8(b). The buckling mode z-axis is shown in the Figure 9(a).

Further, the z-axis deformation for two shells is analyzed in detail and it is represented as a graphical diagram showing the maximum and minimum values (Figure 9b).

On the Z-axis, the maximum displacement value in the cone is 52.994 mm, and the minimum displacement value is −108.798 mm, while in the conoid shell, the max

displacement value is 22.157 mm, and the min displacement value is –52.519 mm.

Then the normal stress analysis is performed. The results are shown in Figures 10 and 11.

The value of normal stresses Nx is less for the conoid shell (max is 373.906 t/m^2, min is –344.572 t/m^2), and for the cone, max is 732.491 t/m^2 and min is –263.996 t/m^2), and the value of normal stresses Ny is less for the conoid (max is 347.432 t/m^2, min is –382.662 t/m^2), and for the cone, max is 669.655 t/m^2 and min is –263.157 t/m^2).

The values of the moment Mx for a cone are greater than for a conoid. The max value is 5.411 t m/m, and the min value is –2.636 t m/m. The conoid max value is 3.422 t/m, and min –2.752 t/m. The smallest value of the moment My has a conoid shell: max is 3.583 t m/m, and min is –1.532 t m/m. The My value of the cone is 5.671 t m/m for max, and –2.761 t m/m for min.

Then the values are obtained for Mxy parameter (Figure 12). The Max value of the cone shell is 1.361 t m/m, and the min value is –1.302 t m/m. For the conoid, the max value is 1.031 t m/m, and the min value is –1.016 t m/m.

It should be noted that all applied loads to the shells are symmetrical. Further, special attention is paid to asymmetric loads. The authors consider the asymmetric snow accumulation. Two load values are set. The load is a trapezoid that varies linearly from a given initial value of P=0.35 t/m to the final value P=0.175 t/m. The deformed scheme is shown in Figure 13 and Figure 14.

On the Z-axis, the maximum displacement in the conoid is –12.839 mm, and the minimum displacement value is –28.925 mm. In the cone shell the max displacement is 16.352 mm, and the min displacement is –29.738 mm. The results are shown in Figure 15.
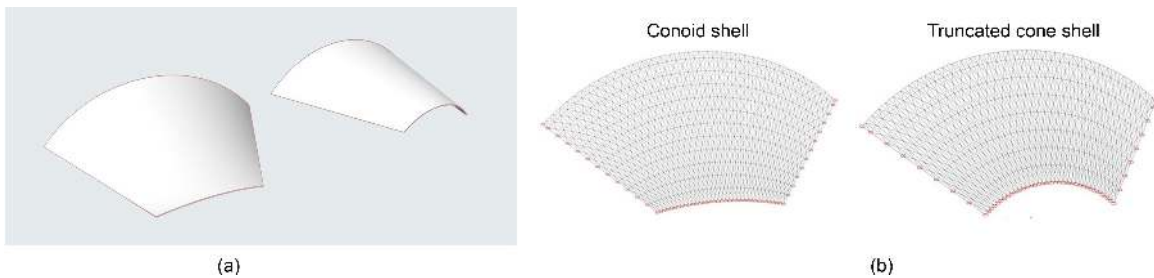

Figure 6: Export models in ArchiCAD to SCAD
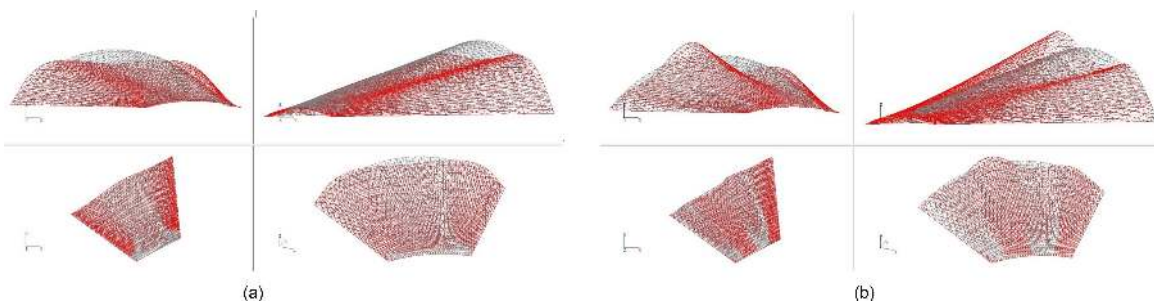
Figure 7: The deformation scheme of conoid shell

Figure 8: The deformation scheme of truncated cone shell
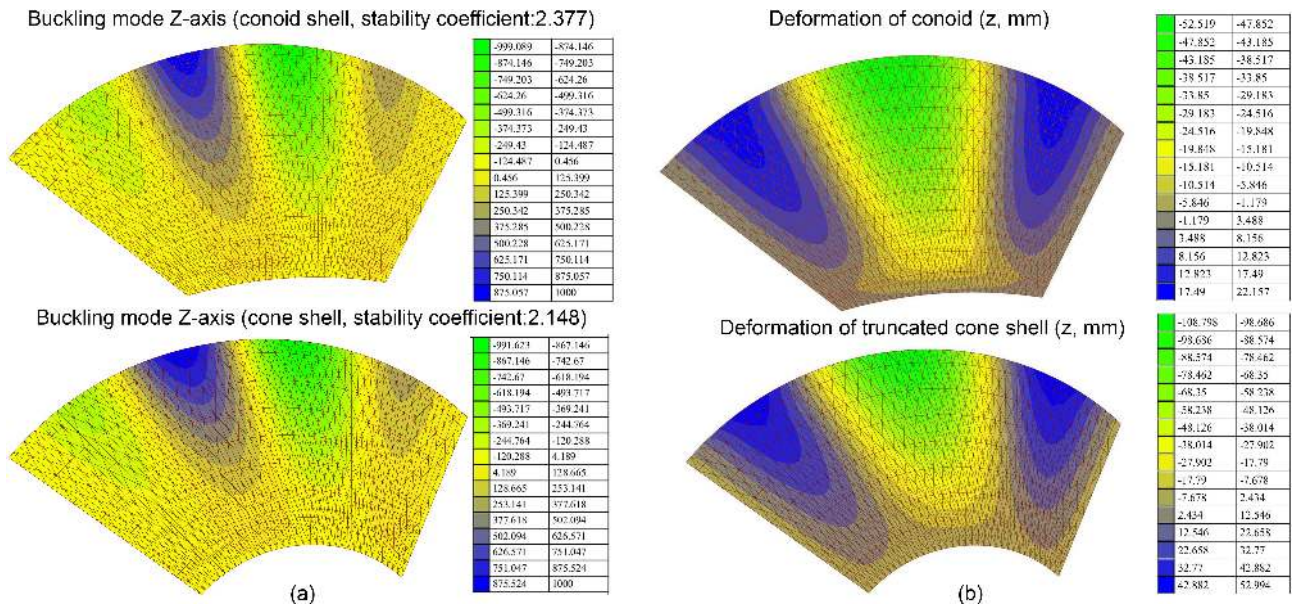
Figure 9: The buckling mode Z-axis (a) and deformation (b) of shells
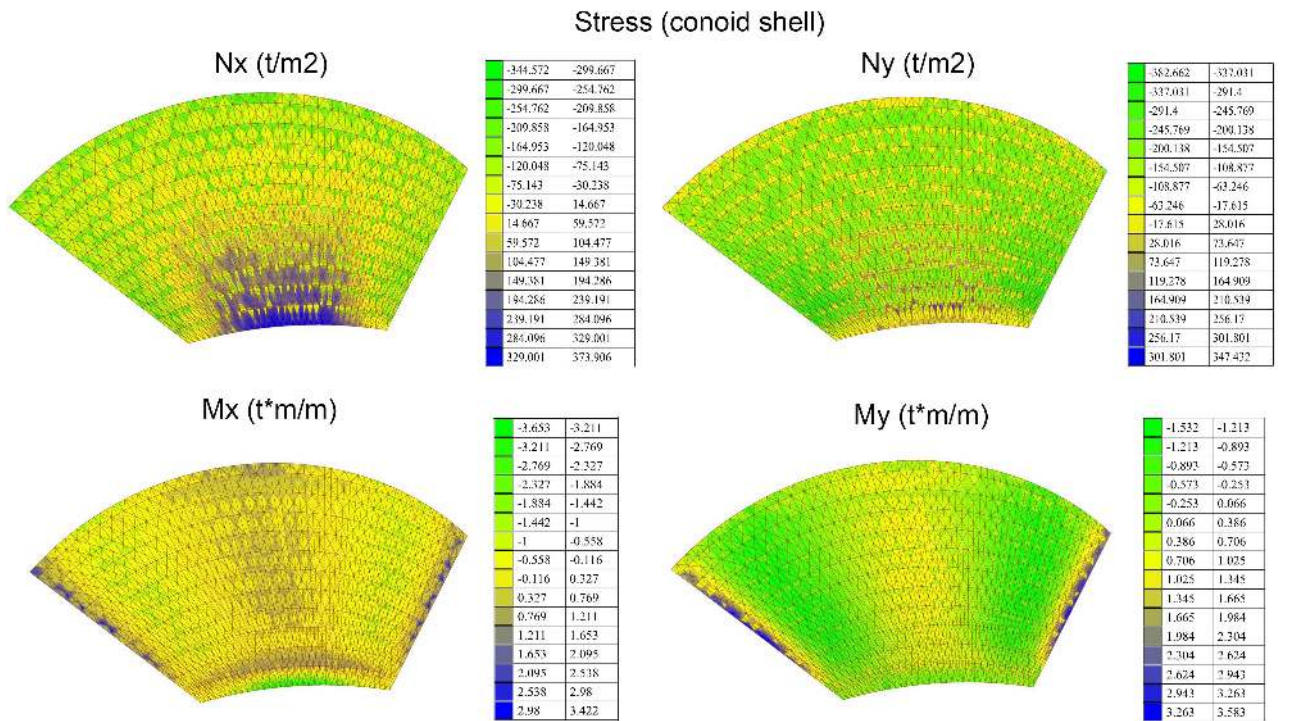
Stress								
Name		Maximum value				Minimum value		
		Value	Element	Section	Combination	Value	Element	Section	Combination
NX	(t/m2)	373.906	2215	1	1	-344.572	4396	1	1
NY	(t/m2)	347.432	3533	1	1	-382.662	3746	1	1
MX	(t*m/m)	3.422	4610	1	1	-3.653	2149	1	1
MY	(t*m/m)	3.583	3068	1	1	-1.532	2974	1	1
MXY	(t*m/m)	1.031	3099	1	1	-1.016	4339	1	1

Figure 10: The normal stresses of the conoid shell

Stress (truncated cone shell)

Nx (t/m2)

-263.996	-201.716
-201.716	-139.435
-139.435	-77.155
-77.155	-14.874
-14.874	47.406
47.406	109.687
109.687	171.967
171.967	234.247
234.247	296.528
296.528	358.808
358.808	421.089
421.089	483.369
483.369	545.65
545.65	607.93
607.93	670.211
670.211	732.491

Ny (t/m2)

-263.157	-204.855
-204.855	-146.553
-146.553	-88.251
-88.251	-29.949
-29.949	28.353
28.353	86.655
86.655	144.957
144.957	203.259
203.259	261.561
261.561	319.863
319.863	378.165
378.165	436.467
436.467	494.769
494.769	553.071
553.071	611.373
611.373	669.675

Mx (t*m/m)

-2.908	-2.388
-2.388	-1.868
-1.868	-1.348
-1.348	-0.828
-0.828	-0.308
-0.308	0.212
0.212	0.732
0.732	1.252
1.252	1.771
1.771	2.291
2.291	2.811
2.811	3.331
3.331	3.851
3.851	4.371
4.371	4.891
4.891	5.411

My (t*m/m)

-3.44	-2.865
-2.865	-2.29
-2.29	-1.715
-1.715	-1.14
-1.14	-0.565
-0.565	0.01
0.01	0.584
0.584	1.159
1.159	1.734
1.734	2.309
2.309	2.884
2.884	3.459
3.459	4.034
4.034	4.609
4.609	5.184
5.184	5.759

Stress										
Name		Maximum value				Minimum value				
		Value	Element	Section	Combination	Value	Element	Section	Combination	
NX	(t/m2)	732.491	1403	1	1	-263.996	2291	1	1	
NY	(t/m2)	669.675	2151	1	1	-263.157	2292	1	1	
MX	(t*m/m)	5.411	2843	1	1	-2.636	1672	1	1	
MY	(t*m/m)	5.671	1897	1	1	-2.761	1713	1	1	
MXY	(t*m/m)	1.361	2097	1	1	-1.302	1906	1	1	

Figure 11: The normal stresses of the truncated cone shell

Mxy (conoid, t*m/m)

-1.016	-0.888
-0.888	-0.76
-0.76	-0.632
-0.632	-0.504
-0.504	-0.377
-0.377	-0.249
-0.249	-0.121
-0.121	0.007
0.007	0.135
0.135	0.263
0.263	0.391
0.391	0.519
0.519	0.647
0.647	0.775
0.775	0.903
0.903	1.031

Mxy (truncated cone, t*m/m)

-1.302	-1.135
-1.135	-0.969
-0.969	-0.802
-0.802	-0.636
-0.636	-0.469
-0.469	-0.303
-0.303	-0.137
-0.137	0.03
0.03	0.196
0.196	0.363
0.363	0.529
0.529	0.696
0.696	0.862
0.862	1.029
1.029	1.195
1.195	1.361

Figure 12: The Mxy parameter of the two shells

Figure 13: The deformation scheme of conoid shell

3 Results and discussion

Considering the obtained values for three parameters, it can be concluded that the shells have quite acceptable values.

The values of the cone deformation are greater than of the conoid shell. The stress values Nx and Ny are less for the conoid. The cone has more Mx values than the conoid, and the conoid shell has the smallest My value. By Mxy values, the cone shell also has the highest value than the cone.
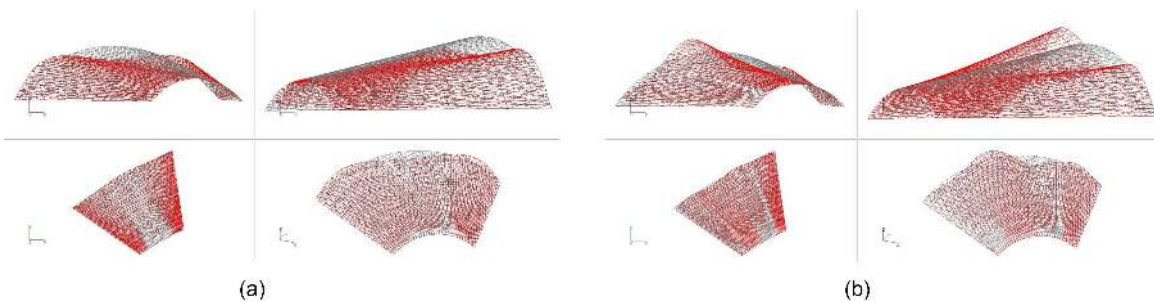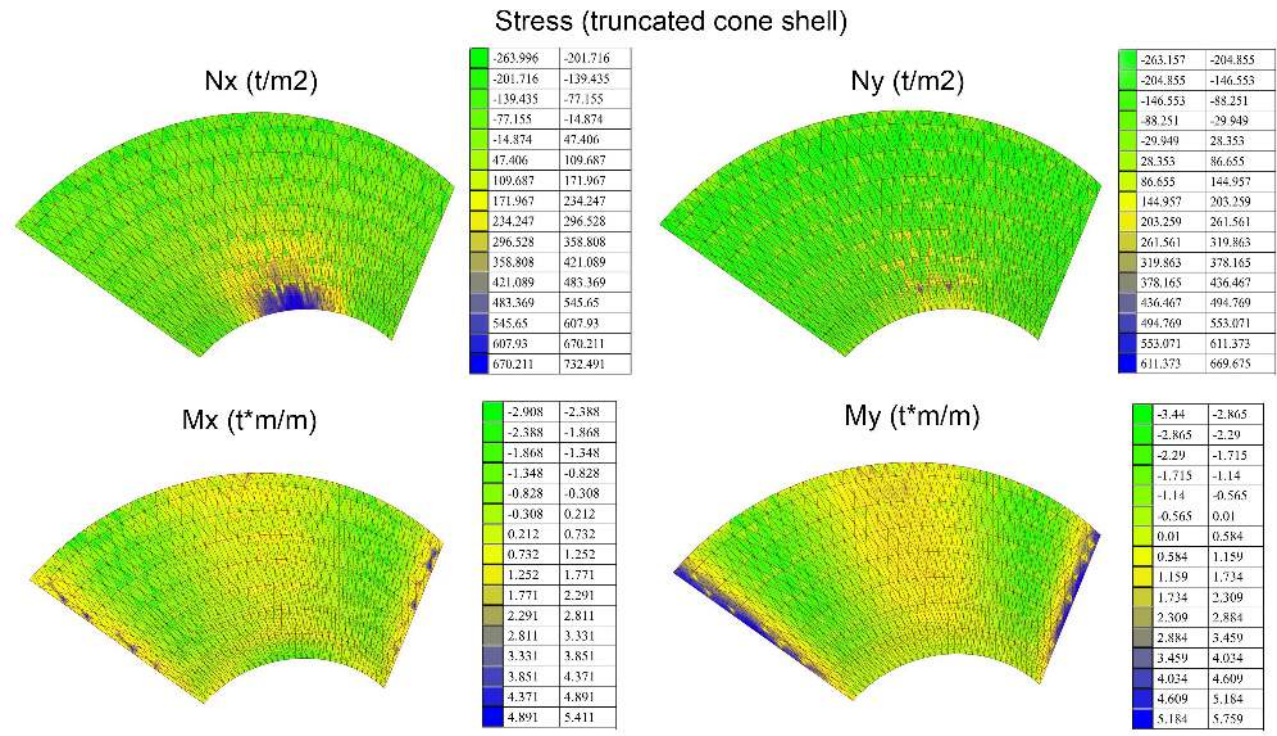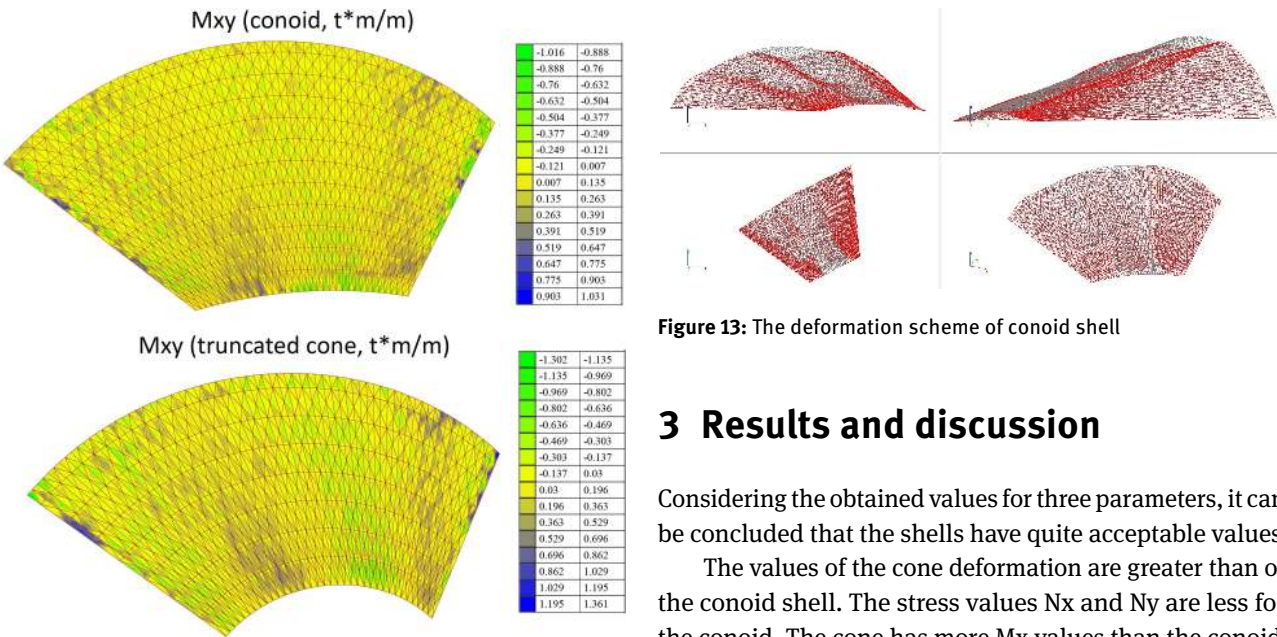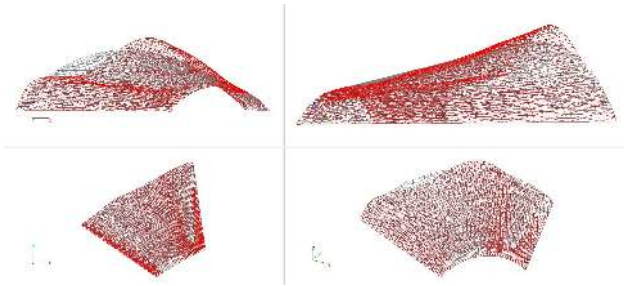
Figure 14: The deformation scheme of truncated cone shell

Figure 15: The z-axis deformation

Figure 16: The project of the concert hall with the use of the conoid surfaces
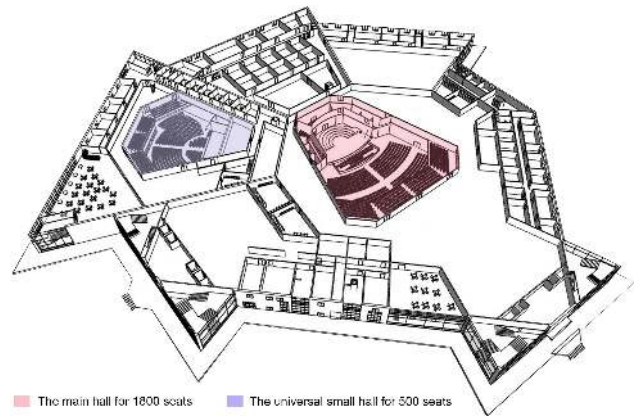
Figure 17: The structure of the concert hall
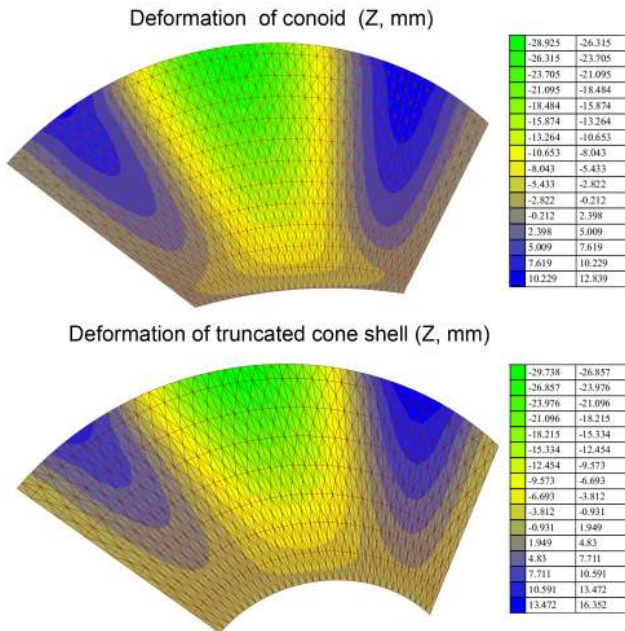
In the case of an asymmetric load, the conoid values are also less.

The conducted research allows to conclude that the best covering of a concert hall is a conoid shell, and the new project based on this shape has been developed (Figure 16).

The structure of the building consists of 3 shells: three surfaces in the form of a conoid with different lifting arrows (18 m, 14 m and 11 m, respectively).

All these elements together form a single composition and create unique concert venues for concerts of various genres: the main hall with 1800 seats for large Symphony concerts and the Small hall with 800 seats for chamber music performances. The structure of the concert hall is shown in Figure 17.

It should be noted that for the future research a method for determining the shape such as dynamic simulation of hanging net (MRA) [18] can be used for the further optimization of a shape. Furthermore, the problem of instability [19–21] will be investigated more widely.
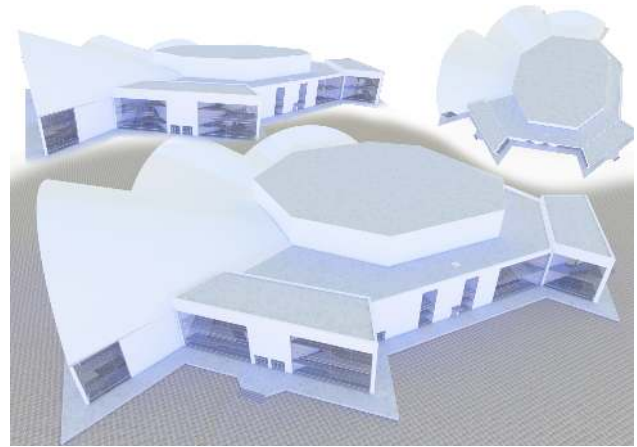
4 Conclusion

It was investigated that the appearance of the concert hall has changed and improved throughout its historical development.

Currently, technologies for designing concert halls include the use of various types of shells. Conoid and truncated cone shells are very widely used in building construction.

The conoid shell was chosen for the appearance of the concert hall, as a result of the study of the stress-strain state of the forms, it was revealed that it experiences less deformation and has lower values of normal stresses and moments than the shell of a truncated cone.

The conoid shell also has a smaller area and requires less material consumption, so its choice, in this case, is most acceptable.

Based on the comparison, a concert hall project was created, which took into account all current trends in architectural planning, structural and acoustic solutions.

Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Conflict of interest: The authors state no conflict of interest.

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