THE BENDING BEHAVIOR OF TWO – DIRECTIONAL CORRUGATED SHELLS

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The general perception about corrugated structures, particularly shells, is that their bending behavior is far superior to the plane ones due to a higher bending stiffness. This study has the objective to highlight the behavior of two two – directional corrugated shells. The reference is a simple flat rectangular shell with identical overall dimensions – length and width. In the first part of the study the thickness is equal for all three model. In the last part, the volume is maintained identical for all three shells by modifying the thickness, as it can result from a manufacturing process.

Keywords: two – directional corrugated shells, bending behavior, hemispherical, bell – shaped.

1. Introduction

Interrogating the search engine Google about „corrugated shells advantages", the exact answer was „Thanks to corrugation, these structures have a remarkable feature: the wavy (undulated) shape in their edge provides significant enhancements in their structural behaviour, increasing the bending stiffness at the edge and allowing for a non-negligible reduction of its thickness.". (www.google.com/search accesed on 20.03.2025 at 19:45) [1], [2].

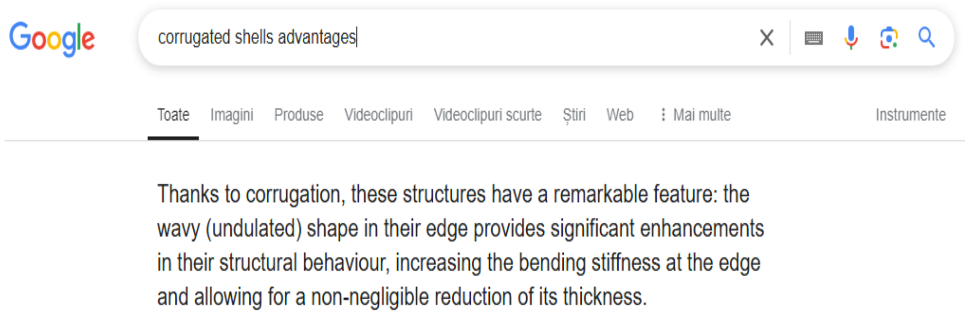

Fig. 1. The Google search return for "corrugated shells advantages" query.

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In the academic comunity is a widely concern to design and, in engineering also to mufufacture, light and stiff structures [3], [4] and [5].

So, this paper will evaluate the bending behavior of two two – directional corrugated shells. The results will be referred to those of a simple flat rectangular shell.

The analysis was made with ANSYS software [6]. All models elements were 4 nodes ”Shell 181” [7].

The material is steel with Young's modulus $E = 210000$ MPa and Poisson's coefficient $\nu = 0.30$.

In figure 2 is presented the reference plate with 120 mm length, 80 mm width and 0.8 mm thickness. Further, it will be reffered as ”modell A”. This simple flat shell is clamped in the left side and loaded on the right end by 17 equidistant forces, each of 0.28 N. Theese values were chosen in such a way that the results will not have signifficant errors. Smaller the results values, higher the errors. The model has 17063 nodes and 16800 elements.

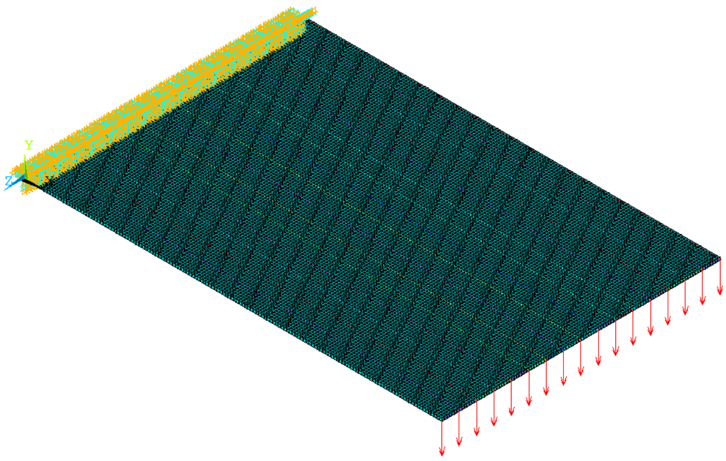

Fig. 2. Model A shell clamped and loaded

2. Corrugated structures

Two corrugated structures were considered and analyzed. Both have the same overall dimensions as the reference model – 120x80, are clamped on the left side and loaded on the right end with 17 equidistant forces of 28 N, as the reference model.

The first one of the corrugated models, further referred as “model B”, is presented in figures 3 and 4.

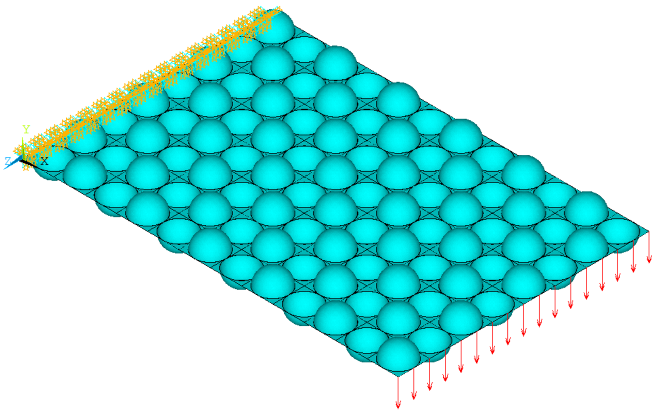

Fig. 3. Model B corrugated shell clamped and loaded

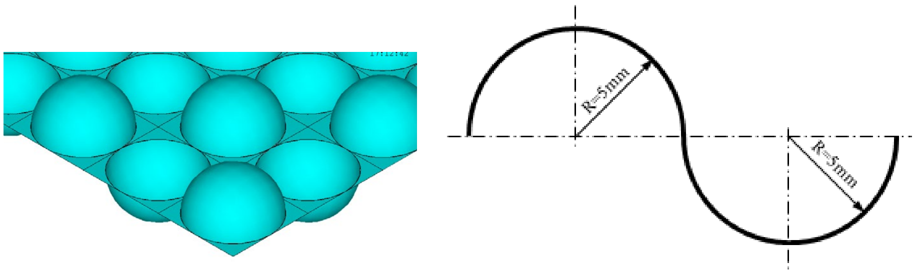

Fig. 4. Detail and geometry of model B corrugated shell

Model B has 34241 nodes and 34584 elements.

Remark. The model was very difficult to mesh in the plane zones, of the hemispheric intersection in a point. This is because they generate a four point star surface with very sharp angles in vertices, as figure 4 reveals.

The second corrugated model, further referred as “model C”, is presented in figures 5, 6 and 7. The corrugation is a bell – shaped one.

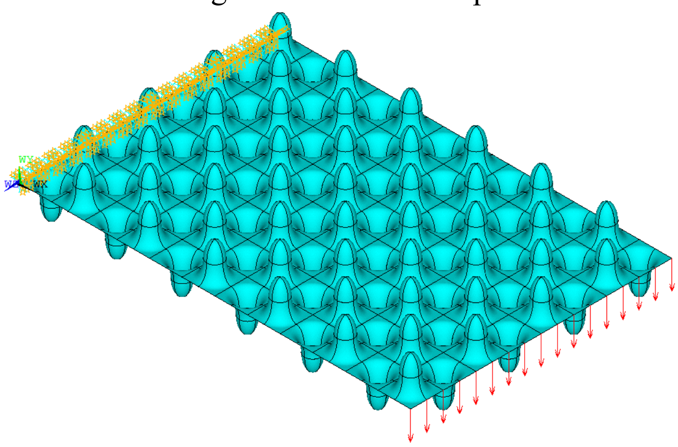

Fig. 5. Model C corrugated shell clamped and loaded

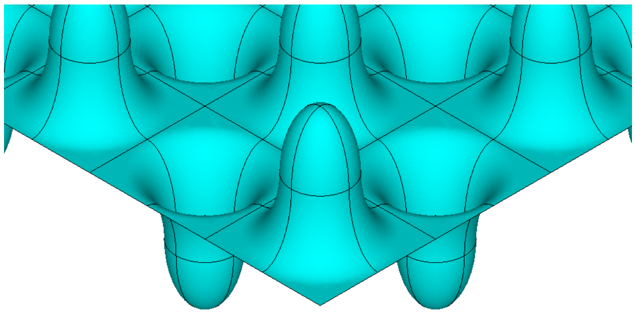

Fig. 6. Detail of model C corrugated shell

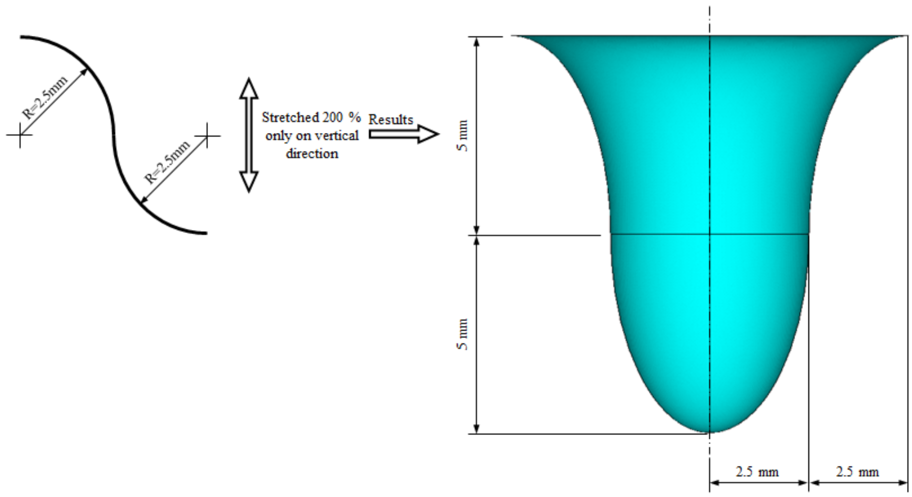

Fig. 7. Geometry of model C corrugated shell

The model C has 68878 nodes and 68528 elements.

Remarks. This model has not supported to be meshed using 8 node "Shell 281" elements due to geometric aspect ratios (small geometry radius related thickness). These curved elements (Shell 281) would have been preferred, because are more suitable for curved structure, being able to "follow" better the real geometry.

The geometry of all three models were successively meshed finer and finer until the convergence of the results was achieved – the gradient of the results values in successive analysis was insignificant. That is why, the different element number of the models must not be a concern. Higher number of elements of the model C, can also be explained by the increased area and small geometry radius which requires more elements in order to achieve the convergence of the results.

3. Analysis and results

Analysis was made in static linear hypothesis.

Considering structures and loads as described above, the first set of results are synthetized in table 1.

Table 1

The Bending Behavior of Simple and Corrugated Shells – Initial variants

Shell variant – Thickness 0.8 mm	Absolute volume [mm^3]	Relative volume [%]	Maximum Von Misses stress [MPa]	Absolute maximum displacements [mm]	Relative maximum displacements [%]
A. Flat rectangular – Reference	7680	100.00	67.07	3.66	100.00
B. Corrugated hemispherical	13737.8	178	90.87	1.55	42.34
C. Corrugated bell – shaped	16209.2	211	74.86	1.72	46.99

The maximum absolute displacements of the shells with a 0.8 mm thickness are presented in figure 7, 8 and 9.

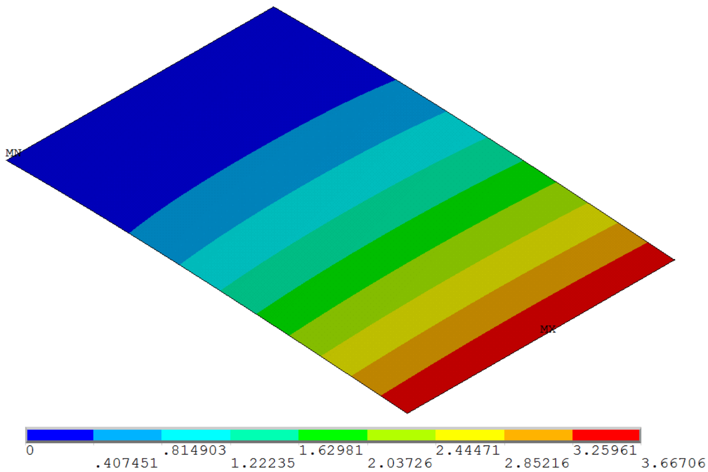

Fig. 7. The maximum displacements of shell A with 0.8 mm thickness

These results offer us relevant and interesting data considering overall dimensions being the same for all three structures – the same length, width and respectively thickness. But, in this case the volumes, and consequently the masses, of the structures are significantly different. Considering that evaluating the bending behavior for the same mass is more relevant, we modified the thickness in order to achieve this effect.

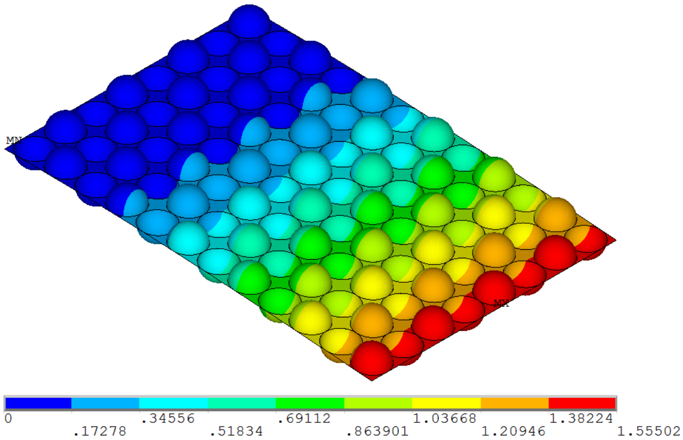

Fig. 8. The maximum displacements of shell B with 0.8 mm thickness

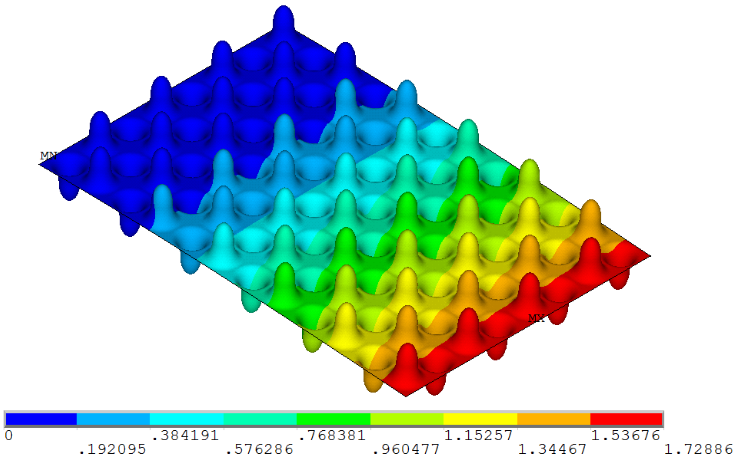

Fig. 9. The maximum displacements of shell C with 0.8 mm thickness

The first step is to bring volumes of the shells A and C to the model B volume value, modifying their thickness. The results of this comparison analysis are presented in table 2.

Table 2

The Bending Behavior of The Type A and C Shells for The Type B Volume

Shell variant – Volume 13737.8 mm^3	Thicknes s [mm]	Maximum Von Misses stress [MPa]	Absolute maximum displacement s [mm]	Relative maximum displacements [%]	Relative rigidity [%]
A. Flat rectangular	1.43	20.95	0.64	41.35	241.83
B. Corrugated hemispherical – Reference	0.8	90.87	1.55	100.00	100.00
C. Corrugated bell – shaped	0.678	101.42	2.66	171.61	58.27

Further we modify the models A and B thickness in order to have the same volumes as the model C. The results are presented in table 3.

Table 3

The Bending Behavior of The Type A and B Shells for The Type C Volume

Shell variant – Volume 16209.2 mm^3	Thicknes s [mm]	Maximum Von Misses stress [MPa]	Absolute maximum displacement s [mm]	Relative maximum displacements [%]	Relative rigidity [%]
A. Flat rectangular	1.688	15.08	0.39	22.67	441.02
B. Corrugated hemispherical – Reference	0.94	66.95	1.00	58.56	170.75
C. Corrugated bell – shaped – Reference	0.8	74.86	1.72	100.00	100.00

Obtaining these unexpected results leads us to compare all three structures at the at the model A volume value, this being the most close to the real situation, resulting from the manufacturing process. Because using the same load, as in the previous analysis, will lead us to stresses beyond yield ones, we will choose to reduce it at a half of previous value. Now, for all shells volume of 7680 mm^3, the load is F=17x0.14 N. The results are presented in table 4.

Table 4

The Bending Behavior of The Type B and C Shells for The Type A Volume and F=2.39N

Shell variant – Volume 7680 mm^3	Thicknes s [mm]	Maximum Von Misses stress [MPa]	Absolute maximum displacement s [mm]	Relative maximum displacements [%]	Relative rigidity [%]
A. Flat rectangular – Reference	0.8	33.53	1.83	100.00	100.00
B. Corrugated hemispherical	0.44	129.49	3.619	197.75	50.56
C. Corrugated bell – shaped	0.379	158.11	6.36	347.54	28.77

The maximum absolute displacements of the shells with a volume of 7680mm^3 (B and C as the shell A) are presented in figure 10 and 11.

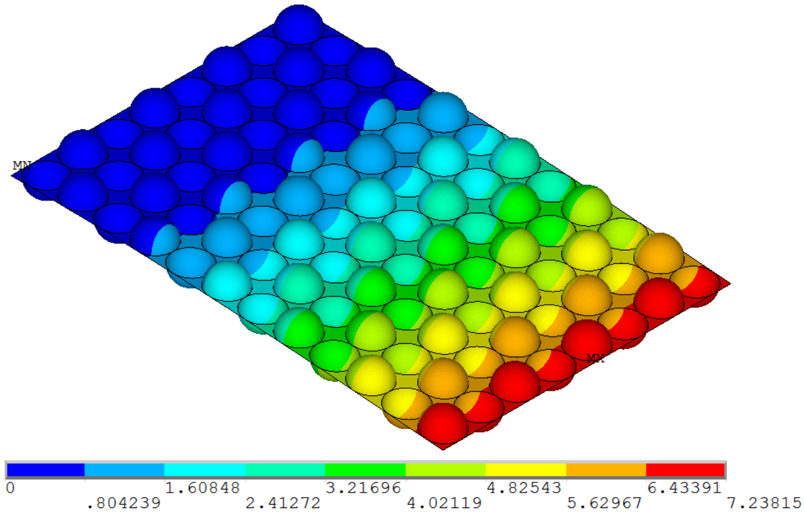

Fig. 10. The maximum displacements of shell B with 0.44 mm thickness

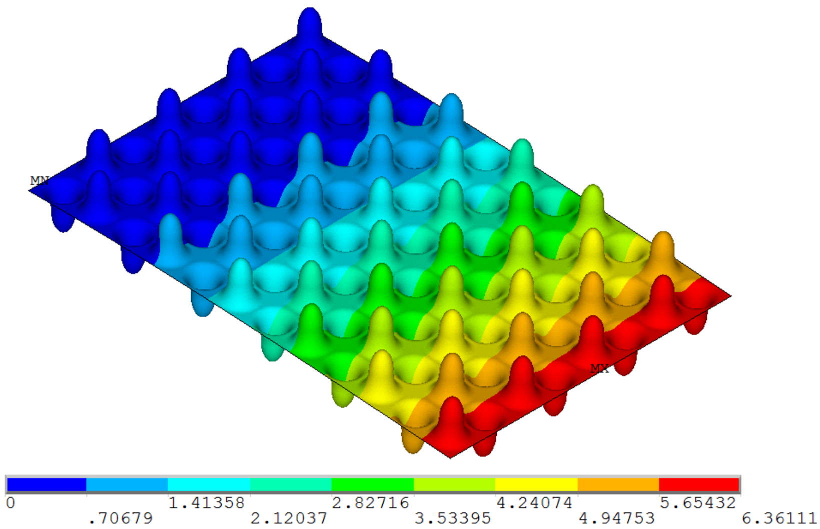

Fig. 11. The maximum displacements of shell C with 0.379 mm thickness

4. Synthesis and result interpretation

Having the previous analysis realized, the results well be evaluated in very simple terms or key: what are the results using the same resources. In this case, the results are the displacements, reflecting the bending behavior, and the resources are the volumes of the structures.

Tables 2, 3 and 4 reveal the same situation, but we will consider the last one, because it is the one which result from the manufacturing situation.

The flat shell is reference one.

The rigidity value is defined as being equal to the load value (force or moment) which produces unity displacement (translation or rotation).

As the fundamental equation of the finite element method is

$$\{F\}=[K]\cdot\{\delta\}, \tag{1}$$

[8] results that, in the scalar form

$$K_{ij}=\frac{F_i}{\delta_j}=\frac{1}{\delta_j}. \tag{2}$$

So, the higher the displacement, the smaller the rigidity.

In table 4, the absolute maximum displacements column, the minimum value is for the flat shell while the maximum for the model C, the bell – shaped one, all for the same load (force). This indicates to us that the flat shell has the highest rigidity considered to be 100 %. It is followed by the hemispherical corrugated shell which rigidity is approximately half of the previous one (50.56 %). The model C corrugated shell, bell – shaped, is the least rigid one with a value of a little bit more than a quarter from the reference flat shell (28.77 %).

5. Conclusions

As it is presented in the Introduction, many authors statue, based on scientific calculus, that the corrugated shells have a higher bending stiffness than their flat counterparts [9], [10]. It is always better to check and validate scientifically these results for the user particular load case, even more so the scientific possibility to perform this is widely available.

At least, in this case, of two two – directional corrugated shells, this latest approach of validating using the science, saves us by falling into the error.

The structural analysis reveals that the flat shell is significantly stiffer than the corrugated shells, approximately twice (more exactly 1.97) than the model B and approximately three and a half times (3.47) than model C, considering the same mass.

In this loading case, the most efficient structure regarding stiffness is the flat shell, being, in the same time, the most quick and also cheap to manufacture due to no need to cold press the blank piece.

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