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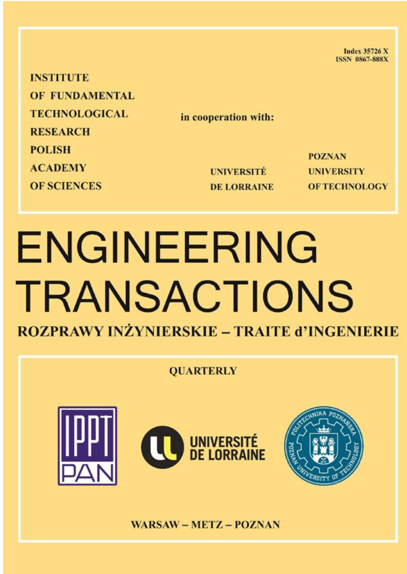


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# Self-Supporting Arch Halls – Design Methods

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Self-supporting arch halls are increasingly used for the construction of buildings with a significant impact on public safety. Unfortunately, no specific design methodology has been established yet. Even more concerning is the growing emergence of new design challenges, including local structural modifications and unconventional loading conditions. This study reviews methods applied in engineering practice as well as those proposed in research studies. A comparative analysis of the results obtained using various methods is presented for selected structures subjected to loads according to applicable standards.

**Keywords**: UBM; K-span; thin-walled panels, arch structures.

## 1. Introduction

Self-supporting arch halls made of doubly corrugated thin-walled steel profiles are becoming increasingly popular in the Polish and European markets. The analysis of recent projects completed by system providers, as presented in [1], indicates that the most commonly constructed buildings in our region are sports halls and agricultural structures, including warehouses, livestock buildings and shelters. Examples of projects completed in 2024 by the Samonośka group [2] using the UBM (Ultimate Building Machine), as described in [3], are presented in Fig. 1-2. Both agricultural and sports facilities often require local structural modifications to meet their functional requirements. In sports halls, skylights (Fig. 3) and ventilation openings are commonly introduced. In agricultural buildings, suspended conveyors, screw carriers, or other equipment is frequently installed. The impact of such local modifications on global structural behaviour is typically not considered during the design process. A probable reason for omitting the influence of these modifications on structural behaviour is the lack of a dedicated design methodology, as previously discussed in various studies, such as [4-6].

## 2. Purpose and scope of work

The aim of this study is to present and compare selected design methods for this type of structure, currently used by engineers or proposed by researchers. A literature review and an analysis of structural design approaches in this field appear necessary, considering the number of structures currently being built, the consequences of structural failures, and the noticeable variation in design approaches observed by the authors. Systematizing knowledge of the fundamental behaviour of self-supporting arch halls will provide a foundation for further research on the impact of local modifications on overall structural performance.

*Fig. 1. Arch hall in Białystok, Poland.*

*Fig. 2. Arch hall in Łomża, Poland.*

*Fig. 3. Skylights in sports halls.*

**3. Review of design methods.**

The selected design methods are presented below. Both methods used in engineering practice (Simplified methods) and those proposed in scientific research (Advanced methods) are described. Based on the author's own research and the conclusions of many researchers (e.g., [7]), it should be emphasized that such structures require the use of second-order theory because they feature the strong nonlinearity.

*3.1. Simplified methods.*

Based on the analysis of projects involving single-shell structures, it has been determined that two primary methods are predominantly used. These methods are classified as simplified due to their lower level of complexity compared to the approaches recommended by researchers specializing in this type of structure.

*Method no.1.*

The first method is based on 1D linear analysis of a single isolated profile and evaluation of its capacity utilisation factor according to the provisions of the Eurocode standards [8], [9], [10]. The cross-section of the profile is analyzed without transverse corrugations and is most often classified as class 4. The buckling length coefficient is assumed in accordance with Annex D of the standard [11].

*Method no.2.*

The second method commonly used in everyday design practice is based on a geometrically non-linear 1D analysis performed for a single profile, with transverse corrugations omitted, similar to the first method. The shape of the arch is deformed by introducing imperfections defined in Annex D of [11]. Following [14], the utilisation factor of capacity assessment is performed at the cross-sectional level, without considering the global buckling factor of the arch.

*3.2. Advanced methods.*

Methods proposed by numerous researchers are classified as advanced because they exhibit a higher level of complexity compared to those used in everyday engineering practice.

*Method no.3.*

In [7], a design approach for these structures was recommended based on 1D models with variable stiffness, which is the result of local buckling of the compressed cross-sectional webs. The necessity of considering additional bending moments arising from the shift in the center of gravity was also highlighted.

*Method no.4.*

A method based on the Finite Element Analysis of shells that takes into account the influence of deformations on the distribution of internal forces. This approach is proposed by many researchers, including [18] and [19].

*Method no.5.*

In the monograph [20], the following method is described. The analysis is based on a 1D model represented by a single profile, which is characterized by variable axial and bending stiffness depending on the bend radius and stresses level. The stiffness values are determined using proposed formulas that account for normal forces, bending moments, and the failure force acting at the centroid of the cross-section. Determining these stiffness values requires laboratory-scale tests or numerical analyses of small-scale shell models. This method has been validated against shell models and laboratory tests, demonstrating a high degree of result convergence.

**4. Discussion.**

The use of the Method no.1 raises doubts for the following reasons. In [12] it was shown that ignoring transverse corrugations can lead to a significant overestimation of the load bearing capacity of the element. The buckling length coefficients given in [10] most frequently do not correspond to the cases considered, especially in relation to UBM technology, which is becoming increasingly popular due to the possibility of introducing a variable bending radius of the arch. Furthermore, in [7] it was observed that the buckling length coefficient should be determined considering the variable stiffness of the arch. When designing in accordance with this approach, the additional stress on the structure resulting from the change in its geometry under load is not considered [13].

In relation to the assumptions of the Method 2, based on the results shown in [15], self-conducted measurements of actual imperfections were made on structures with shapes corresponding to those defined in [11]. Measurements were carried out after the arches were installed, before additional loads and in wind-free conditions, using a Leica 3D Disto laser rangefinder [16]. The results indicate significantly greater deformations in the real structures than those assumed in the standard [10]. The measurements in-plane of arch are illustrated in Figs. 4 and 5, while out-of-plane are illustrated in Fig. 6. The results are presented as follows: line (1) represents the theoretical arch shape; line (2) represents the curve derived from imperfections according to [11] and static calculations under self-weight; line (3) represents the curve obtained from actual measurements. The measurement results are provided for sections 1 to 5, which are located at 30-degree intervals. The displacements are measured relative to the Line 1 (red line – theoretical shape without imperfections). Furthermore, the measurements revealed a tendency for profiles with larger spans (L>18 m) to undergo lateral (out-of-plane) displacements in the ridge zone (the top zone – the highest part of the structure), as shown in Fig. 6. The red points shown in Fig. 6 indicate the locations of successive measurements taken in the vertical plane. The red font numbers in Fig. 6 correspond to the measurement point numbers. As shown in the Fig. 6, the maximum measured out-of-plane displacement of the panel is 71 mm. These findings highlight potential discrepancies between assumed and actual structural behavior, indicating that the imperfections prescribed in [11] may underestimate the real deformations that occur in the self-supporting arch halls. Table 1 presents the measured imperfection values of the halls, which are illustrated in Figs. 4, 5 and 6.

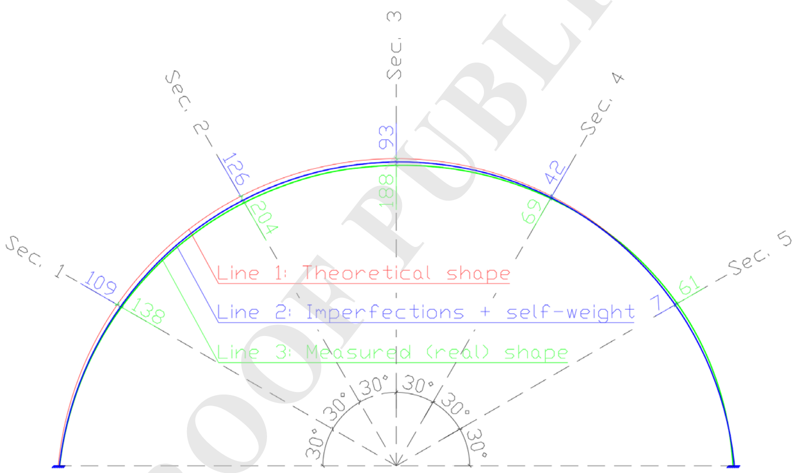



*Fig. 4. Measurements of the shape of the first roof covering, with a span of 19 meters.*

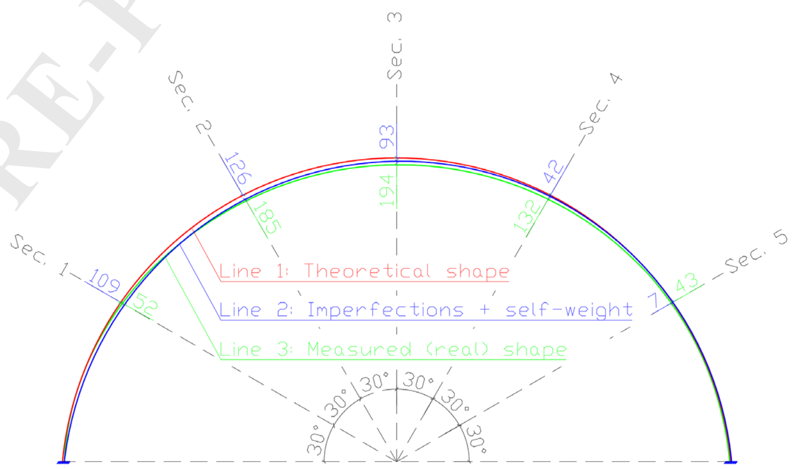
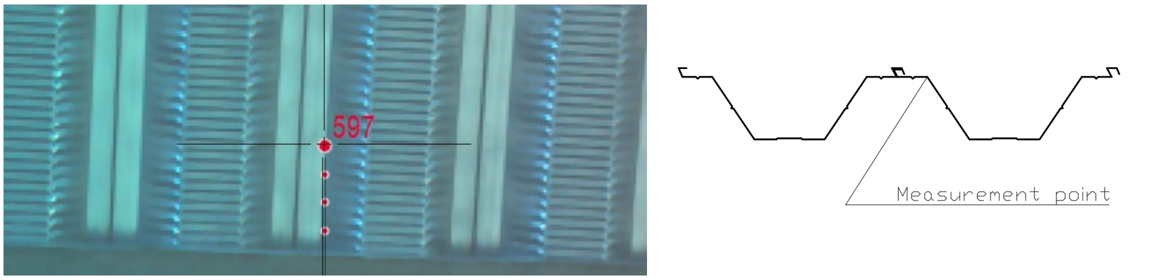
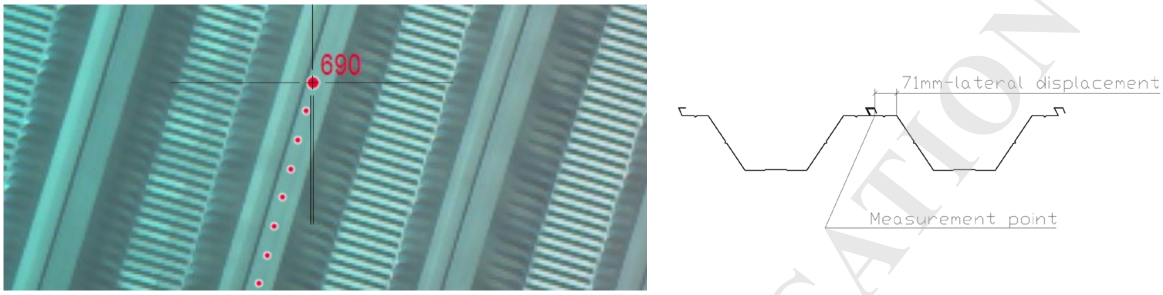



*Fig. 5. Measurements of the shape of the second roof covering, with a span of 19 meters.*




*Measurement in the support zone.*




*Measurement in the ridge zone.*

*Fig. 6. Lateral displacements.*

Table 1. Measurement of the shape of arch-hall with span of 19 meters.

| Analyzed structure | Location along the panel | Displacement in-plane [mm] | | Displacement out-of-plane [mm] | |
|---|---|---|---|---|---|
| | | Case 1* | Case 2** | Case 1* | Case 2** |
| Structure no. 1 acc. to Fig. 4 | Sec. 1 acc. to Fig. 4 | 109 | 138 | 0 | 27 |
| | Sec. 2 acc. to Fig. 4 | 126 | 204 | 0 | 51 |
| | Sec. 3 acc. to Fig. 4 | 93 | 188 | 0 | 71 |
| | Sec. 4 acc. to Fig. 4 | 42 | 69 | 0 | 45 |
| | Sec. 5 acc. to Fig. 4 | 7 | -61 | 0 | 20 |
| Structure no. 2 acc. to Fig. 5 | Sec. 1 acc. to Fig. 5 | 109 | 52 | 0 | 15 |
| | Sec. 2 acc. to Fig. 5 | 126 | 185 | 0 | 29 |
| | Sec. 3 acc. to Fig. 5 | 93 | 194 | 0 | 42 |
| | Sec. 4 acc. to Fig. 5 | 42 | 132 | 0 | 32 |
| | Sec. 5 acc. to Fig. 5 | 7 | 43 | 0 | 19 |

*Case 1 refers to the comparison between the ideal shape (Line 1 acc. to Fig. 4 and 5) and the deformed shape obtained from calculations after introducing imperfections and applying self-weight (Line 2 acc. to Fig. 4 and 5).

**Case 2 refers to the comparison between the ideal shape (Line 1 acc. to Fig. 4 and 5) and the actual shape obtained from measurements (Line 3 acc. to Fig. 4 and 5).

With respect to advanced methods, Method No. 3 does not provide a definition of the geometric characteristics for elements with transverse corrugations. As demonstrated in [17], these characteristics differ from those of elements with flat walls and additionally depend on the introduced bending radius. Method No. 4 may soon become the industry standard, given technological advancements and the increasing computational power of standard computers. However, the authors emphasize that further refinement is needed, particularly in defining the geometry of doubly corrugated profiles. Currently, panel geometry is most often defined based on 3D scans. This approach complicates comparative analyses, which structural designers frequently conduct during the design phase to select the most optimal solution. Moreover, it requires access to the analyzed profiles, which are not commonly available in most design offices.

Based on the authors' literature study, Method no.5 presented in [20], appears to be the most optimal approach given the current state of knowledge. Further study of this method is recommended for designers working with such structures.

## 5. Comparison of selected methods

Comparing the results obtained using conventional (simplified) methods with those of suggested (advanced) methods is not a common practice, especially when the analyzed structure is subjected to loads defined by design standards. In [20] it was stated that, engineering methods overestimated load capacity by 25% and underestimated the deflection by more than three times. However, these results were obtained for a single case of symmetric load rather than for a combination of primarily asymmetric loads. The following section presents the results of own analyses. The first analysis concerns a structure with constant bending radius, the geometry of which is shown in Fig. 7, subjected to loads as illustrated in Fig. 8. Finishing materials assumed as 0,3 kN/m$^2$. Wind loads were applied in accordance with standard [21] for the following assumptions: localization Poland, 1$^{st}$ wind zone, 4$^{th}$ terrain category. Snow loads followed standard [22] for the following assumptions: localization Poland, 2$^{nd}$ snow zone. The analyzed model is a 1D bar model, with pinned supports and a cross-section of the UBM240 system, as shown in Fig. 9.

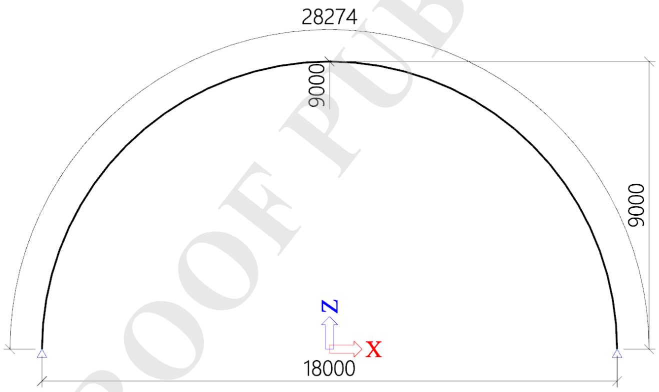
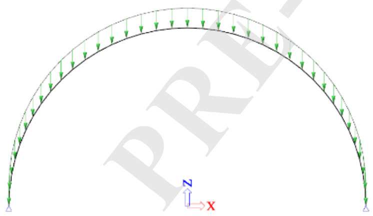
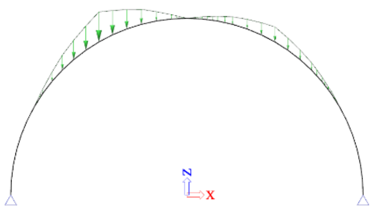


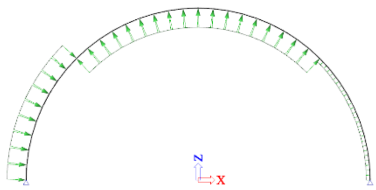

*Fig. 7. Analyzed structure.*



*Load case 1: Self-weighting and finishing material load.*



*Load case 2: Snow load.*



*Load case 2: Wind load.*

*Fig. 8. Analyzed load cases.*

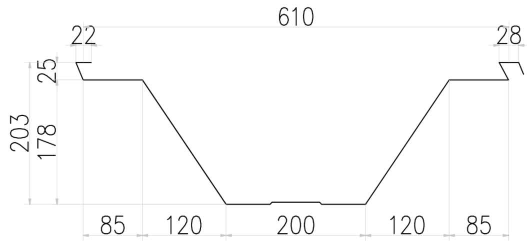
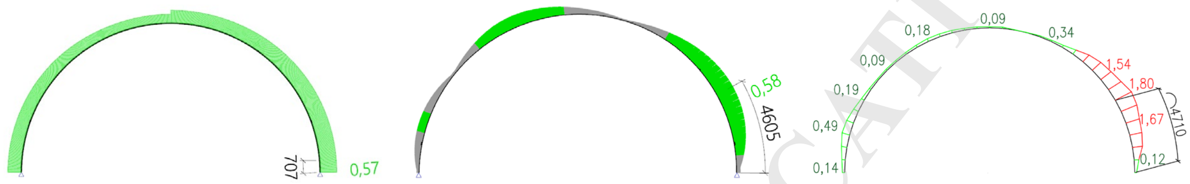



*Fig. 9. Analyzed cross-section: UBM240 t=1,40 mm S320GD+Z.*

Calculations were performed for load combinations according to the standard [8], using the simplified methods (Method no. 1 and 2) described above, as well as the Method no. 5. Figure 10 illustrates the use of the arches' capacity. Table 2 provides a summary of the results.




*Method No.1 (simplified).* *Method no.2 (simplified).* *Method no.5 (advanced).*

*Fig. 10. Results obtained - Utility of capacity for load combination.*

Table 2. Obtained results.

| Design method | Obtained results | | | | | |
|---|---|---|---|---|---|---|
| | Displacement $U_x$ | | Displacement $U_z$ | | Utility of capacity UC | |
| | Value [mm] | Section* [m/m] | Value [mm] | Section* [m/m] | Value [%] | Section* [m/m] |
| Method no.1 (simplified) | 81,4 | 6,67/28,27 | 48,8 | 17,32/28,27 | 57,0 | 0,71/28,2 |
| Method no.2 (simplified) | 86,2 | 6,77/28,27 | 50,6 | 17,41/28,27 | 58,0 | 4,61/28,27 |
| Method no.5 (advanced) | 560,8 | 5,93/28,27 | 304,7 | 16,93/28,27 | 180,0 | 4,71/28,27 |

* *Section measured from the right support.*

Due to the increasing popularity of self-supporting roofs with variable bending radius, the second analysis was performed for a structure with the geometry shown in Figure 11. An analogous approach was adopted as in the first case. Figure 12 illustrates the loading method, while Figure 13 presents the utilization of the arches' capacity. Table 3 provides a summary of the results.

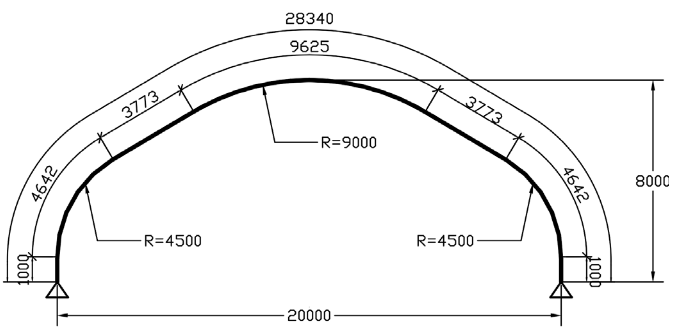
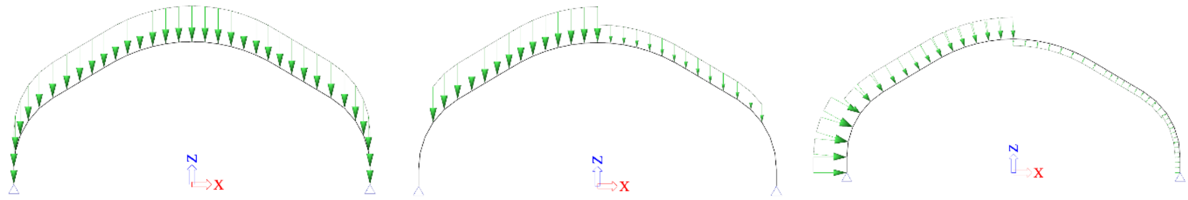
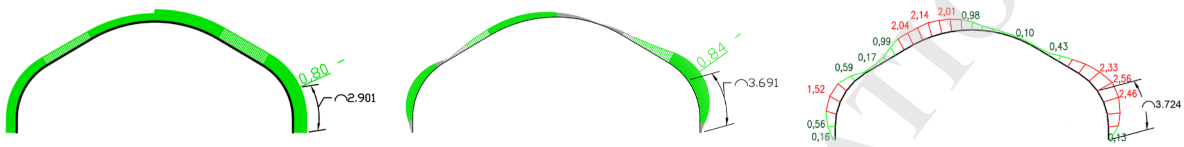



*Fig. 11. Analyzed structure.*




*Load case 1: Self-weighting and finishing material load.* *Load case 2: Snow load.* *Load case 2: Wind load.*

*Fig. 12. Analyzed load cases.*




*Method No.1 (simplified).* *Method No.2 (simplified).* *Method No.5 (advanced).*

*Fig. 13. Results obtained: Utility of capacity for load combination.*

Table 2. Results obtained.

| Design Methods | Obtained results | | | | | |
|---|---|---|---|---|---|---|
| | Displacement $U_x$ | | Displacement $U_z$ | | Utility of the capacity | |
| | Value [mm] | Section* [m/m] | Value [mm] | Section* [m/m] | Value [%] | Section* [m/m] |
| Method No.1 (simplified) | 73,6 | 5,30/28,34 | 64,6 | 16,77/28,34 | 80,0 | 2,90/28,34 |
| Method No.2 (simplified) | 79,4 | 5,45/28,34 | 68,5 | 16,82/28,34 | 84,0 | 3,69/28,34 |
| Method No.5 (advanced) | 710,1 | 3,97/28,34 | 589,7 | 15,19/28,34 | 256,0 | 3,72/28,34 |

* *Section measured from the right support.*

**6. Summary**

Designing self-supporting arch halls made of doubly corrugated thin-walled steel profiles based on inadequately adjusted methods can lead to a significant overestimation of load bearing capacity and an underestimation of deflections. The discrepancy in the results essentially excludes the possibility of using simplified methods with the current state of knowledge. More research, focused on considering local modifications, real imperfections, and tendencies to lateral displacements, seems necessary to conduct.

**7. Declaration of Conflict of Interest**

The authors declare that there are no known competing financial interests or personal relationships that could influence the work reported in this document.

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