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Research Paper

Self-Supporting Arch Halls – Design Methods

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Self-supporting arch halls are increasingly used in the construction of buildings with a significant impact on public safety. Unfortunately, no specific design methodology has yet been established. 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 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. An 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 World Technology Group [2] using the ultimate building machine (UBM), as described in [3], are presented in Fig. 1 and Fig. 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 are frequently installed. The impact of such local modifications on global structural behavior is typically not considered during the design process. A probable

FIG. 1. Arch hall in Białystok, Poland.

FIG. 2. Arch hall in Łomża, Poland.

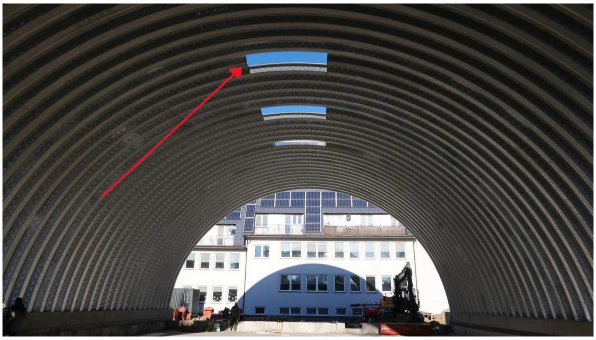


FIG. 3. Skylights in sports halls.

reason for omitting the influence of these modifications on structural behavior 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 behavior of self-supporting arch halls will provide a foundation for further research on the impact of local modifications on overall structural performance.

3. Review of design methods

The selected design methods are presented further. Both methods used in engineering practice (simplified methods) and those proposed in scientific research (advanced methods) are described. Based on the authors' 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 exhibit strong nonlinearity.

3.1. Simplified methods

Based on an 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. Simplified methods include:

- method no. 1: based on a 1D linear analysis of a single isolated profile and an evaluation of its capacity utilisation factor according to the provisions of the Eurocode standards [8–10]. 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: commonly used in everyday design practice is based on a geometrically nonlinear 1D analysis performed for a single profile, with transverse corrugations omitted, similarly 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 for capacity assessment is determined 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. Advanced methods include:

- method no. 3: a design approach proposed in [7], 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: based on the finite element analysis of shells and takes into account the influence of deformations on the distribution of internal forces. This approach has been proposed by many researchers, including [18, 19];
- method no. 5: described in the monograph [20], based on a 1D model represented by a single profile, characterized by variable axial and bending stiffness depending on the bend radius and stress 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 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 while considering the variable stiffness of the arch. When designing in accordance with this approach, the additional stresses in the structure resulting from changes in its geometry under load are not considered [13].

In relation to the assumptions of method no. 2, based on the results shown in [15], self-conducted measurements of actual imperfections were conducted on structures with shapes corresponding to those defined in [11]. The measurements were carried out after the arches were installed, before additional loads and under 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 in-plane measurements of the arch are illustrated in Fig. 4 and Fig. 5, while the out-of-plane ones 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; and 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 line 1 (red line – the theoretical shape without imperfec-

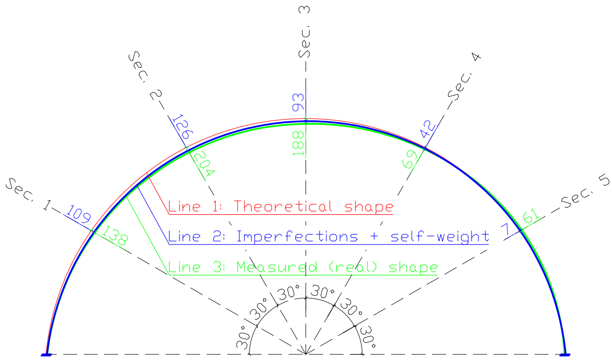


FIG. 4. Measurements of the shape of the first roof covering, with a span of 19 m.

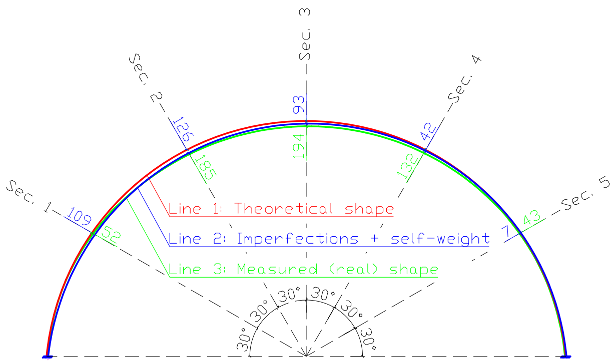


FIG. 5. Measurements of the shape of the second roof covering, with a span of 19 m.

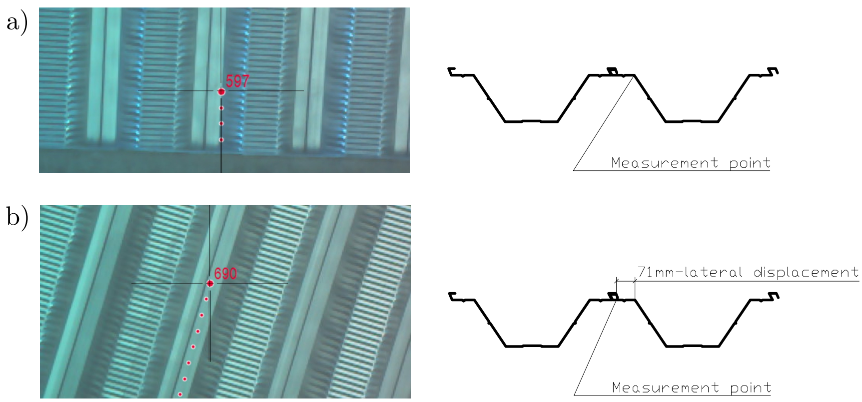


FIG. 6. Lateral displacements – measurement in the support zone (a) and ridge zone (b).

tions). 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 numbers in Fig. 6 correspond to the measurement point identifiers. As shown in 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 self-supporting arch halls. Table 1 presents the measured imperfection values of the halls illustrated in Fig. 4, Fig. 5, and Fig. 6.

TABLE 1. Measurement of the shape of an arch-hall with a span of 19 m.

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 according (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 Fig. 5) and the deformed shape obtained from calculations after introducing imperfections and applying self-weight (line 2 acc. to Fig. 4 and Fig. 5).
**Case 2 refers to the comparison between the ideal shape (line 1 acc. to Fig. 4 and Fig. 5) and the actual shape obtained from measurements (line 3 acc. to Fig. 4 and Fig. 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 the 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 the authors' own analyses. The first analysis concerns a structure with constant bending radius, the geometry of which is shown in Fig. 7, subjected to the loads illustrated in Fig. 8. Finishing materials assumed as $0.3\,\mathrm{kN/m^2}$. Wind loads were applied in accordance with standard [21] for the following assumptions: localization Poland, 1st wind zone, and 4th terrain category. Snow loads followed standard [22] for the following assumptions: localization Poland, and 2nd 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.

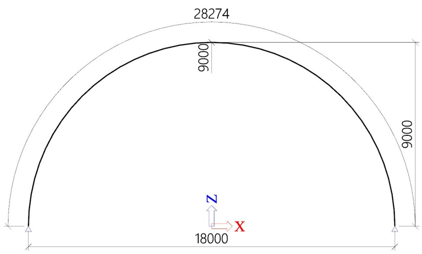
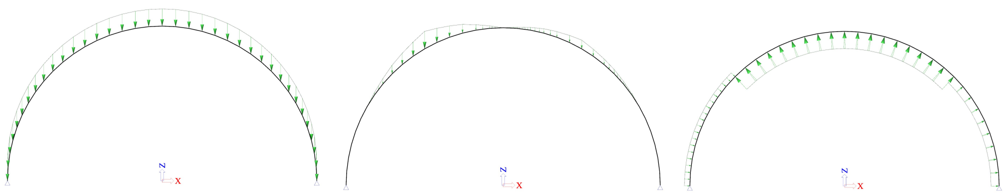


Fig. 7. Analyzed structure.



Load case 1:
Self-weigh and finishing material load

Load case 2:
Snow load

Load case 2:
Wind load

Fig. 8. Analyzed load cases.

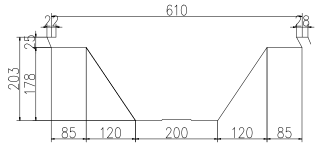


FIG. 9. Analyzed cross-section: UBM240 $t = 1.40$ mm, S320GD+Z.

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

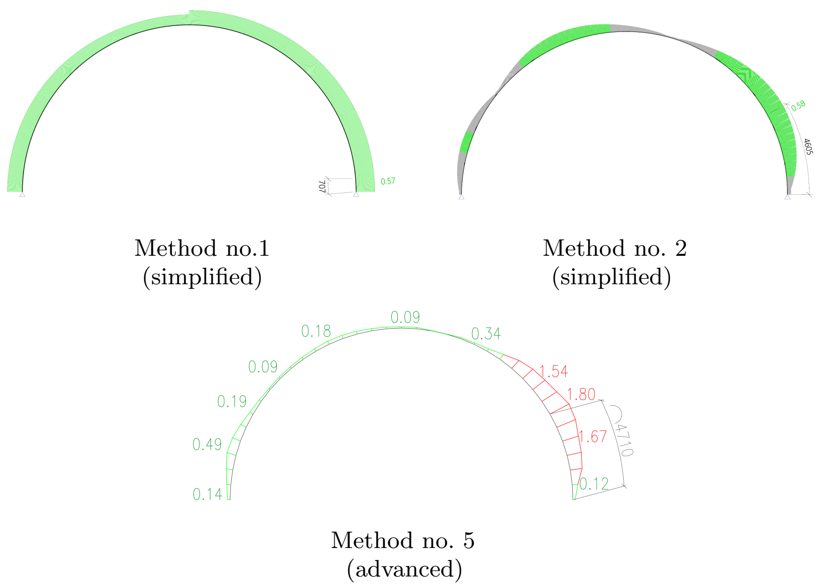


FIG. 10. Results obtained – utilization of capacity for the load combination.

TABLE 2. Obtained results.

Design method	Obtained results					
	Displacement U_x		Displacement U_z		Utilization 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	0.71/28.27
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 a variable bending radius, a second analysis was performed for a structure with the geometry shown in Fig. 11. An analogous approach to that in the first case was adopted. Figure 12 illustrates the loading method, while Fig. 13 presents the utilization of the arches' capacity. Table 3 provides a summary of the results.

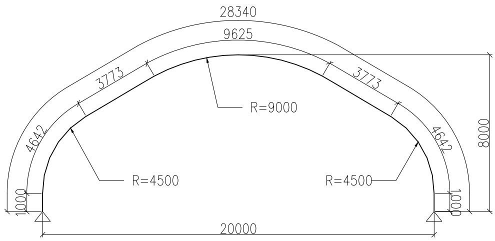
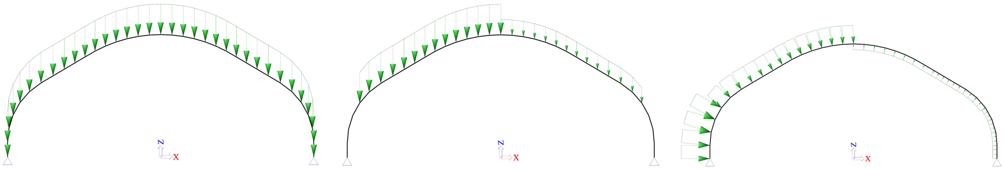


FIG. 11. Analyzed structure.

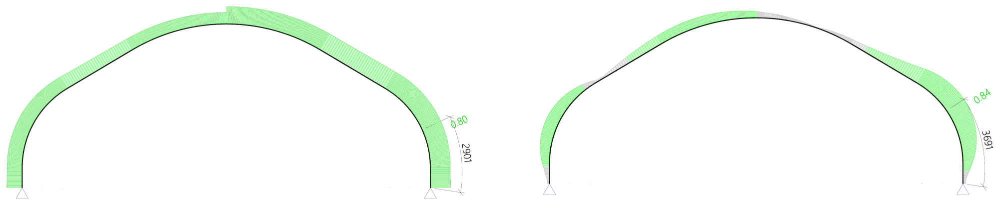


Load case 1:
Self-weigh and finishing material load

Load case 2:
Snow load

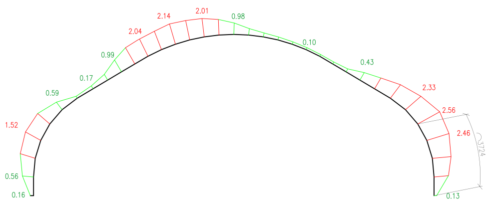
Load case 2:
Wind load

FIG. 12. Analyzed load cases.



Method no.1
(simplified)

Method no. 2
(simplified)



Method no. 5
(advanced)

FIG. 13. Results obtained – utilization of capacity for the load combination.

TABLE 3. Obtained results.

Design method	Obtained results					
	Displacement U_x		Displacement U_z		Utilization of capacity UC	
	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 given the current state of knowledge. More research, focused on considering local modifications, real imperfections, and tendencies toward lateral displacements, seems necessary to be conducted.

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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.

AUTHORS' CONTRIBUTIONS

Ryszard Walentyński conceptualized the study and supervised the study. Robert Cybulski contributed to data interpretation and supervised the study. Henryk Myrcik performed the analysis and wrote the original draft. All authors reviewed and approved the final manuscript.

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