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Review paper

Experimental and computational approaches to the evaluation of double corrugated arch structures. A review of the latest advancements

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Abstract: Double corrugated, self-supporting K-span arch structures are now commonly used globally to make roofs for building structures, as an alternative to traditional solutions. The K-span system has become popular mainly due to the simple and cheap method of its manufacturing and quick installation. Nowadays, new versions of the system are created but still there is no valid design method. Design difficulties are among the causes of failures or even collapses of such structures. Back in the 1970s, the first studies were developed concerning computational analyses of double corrugated arch roofs. They laid grounds for the development of contemporary K-span system technology but have since lost their practical advantages due to changing engineering conditions. The paper presents a review of research and computational methods concerning double corrugated arch structures. The paper discusses selected scientific studies, which were used as the basis for the development of research and computational methods, and their contemporary continuation. Directions for further research and analyses are also presented which could contribute to the future development of science and engineering in the area and could provide inspiration for future studies.

Keywords: K-span, arch structures, double corrugated steel sheets, imperfections, Digital Image Correlation, Finite Element Method

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1. Introduction

Arch covers made of thin steel sheets known as Quonset Hut [1] and [2] were created in the 1940s in response to the army's demand for lightweight, quick and easy-to-mount temporary structures intended for immediate military needs. The concept of Quonset Hut development based on the previous Nissen Bow Hut assumptions [2] and [3] was accurately determined by the requirements of the British army and addressed two essential issues, i.e. the structure should have an arched roof to ensure proper rigidity and load capacity and its installation should be easy and quick. The directions of the system development were oriented towards obtaining a structure which is cheap to produce and easy to install. The concept of temporary buildings with arched roofs evolved towards permanent use in civil engineering. It was initially used for civil engineering purposes in farm and warehouse buildings. Then, the system was gradually modified, which resulted in the development of self-supporting arch structures made of double corrugated sheets, which are now known as K-span. Fig. 1a) presents a historical photo of a Quonset Hut system facility mounting in 1942, while Fig. 1b) shows the mounting of a contemporary K-span facility.

K-span has been used in the global construction market for nearly eighty years now. It owes its popularity to a simple structure, and functional and economic advantages. Nowadays, arch components are made by mobile rolling machines mounted on site, which greatly accelerates the building process.

Contemporary double corrugated construction systems are created by combining single profiles with a trapezoidal or rectangular cross-section, made by cold rolling of steel sheets with a nominal thickness from 0.5 mm to 1.5 mm. Rolling is performed in two stages. In the first stage, a straight section with an extrusion-moulded cross-section (trapezoid or rectangular) is formed, while in the second stage the profile is curved by transverse corrugation of the flanges and web, which allows for obtaining a circular arch shape with the right radius. The name "double corrugated profiles" derives from the double process of shaping the profiles, which was first used by Mang in papers [4] and [5]. Once shaped, the profiles are combined into packages and then merged into a continuous cylindrical structure – Fig. 1b.

Fig. 1. Double corrugated arch structure facilities, a) historical photo presenting the Quonset Hut system facility mounting [1], b) K-span system roof structure assembly [6]

Nowadays, several variations of K-span systems are marketed globally. They differ in their manufacturing method. One of the K-span system variations is the Automatic Buildings Machine (ABM), in which single profiles are made by a mobile rolling machine from one steel sheet directly on site. The profiles are combined into packages, which are then blended to create a continuous rolled cover with no supporting structure. ABM enables the making of several dozen types of profiles with different cross-section shapes. The most common ones include ABM 240 (Fig. 2) and ABM 120 (Fig. 3).

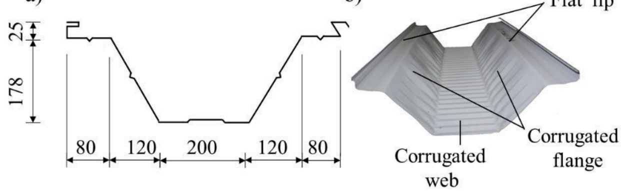

Fig. 2. K-span system, ABM 240 variation, a) cross-section, b) profile view after rolling

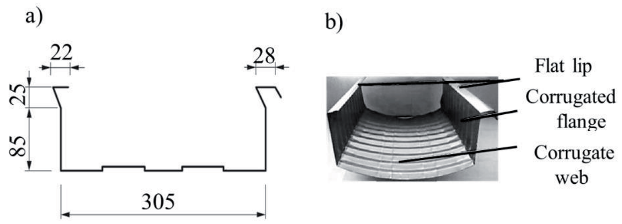

Fig. 3. K-span system, ABM 120 variation, a) cross-section, b) profile view after rolling

ABM 240 version allows the making of circular arch covers with a span of up to 36 m, while in the case of ABM 120 the span amounts to 24 m. The production and integration of K-span system versions is identical.

Another variation, called TG Buildings, is also composed of self-supporting circular arch elements but it is made as prefabricated profiles, usually 3 m long and from 1.5 mm thick steel sheets, which are connected with bolts. The variation helps to build arch roofs with a span of up to 42 m.

The abovementioned variations of the K-span system constitute only a minor part of the drawing range of such structures. Each variation contains dozens of modifications with different shapes, dimensions of the tray profile, corrugation kind and application range with regard to the acceptable arch span and rise.

Regardless of the analysed variations of the K-span system, they all share one feature. There are deep transverse ribs on the web surface, which are formed in the second stage of rolling, i.e. during profile curving. The presented feature of K-span system profiles makes it difficult to apply the rules presented, among others, in European standards [7], [8], [9] and [10] for designing because none of the standards covers such surface shape characteristics.

Design difficulties related to lack of standard computational methods could contribute to failures and collapses of K-span system arch structures. An example of the K-span hall disaster is shown in fig. 4a) Tuszyn (Poland).

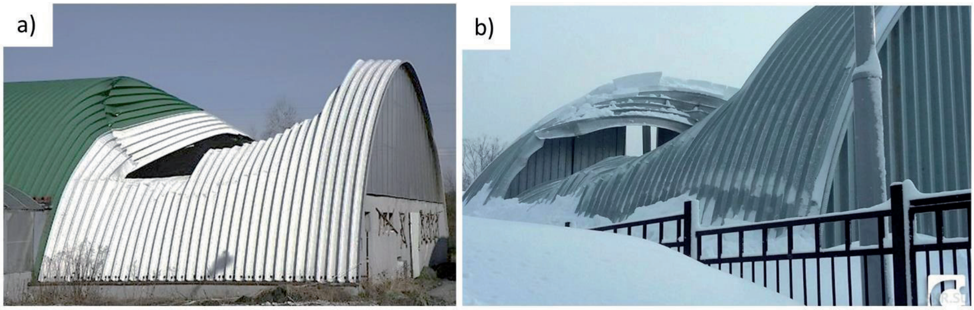

Fig 4. Collapse of the hall roof, a) Tuszyn (Poland), b) Yuzhno-Sakhalinsk (Russia) [14]

A case of wrong design is presented in a paper by A. Biegus and A. Kowal [11]. According to the authors of the paper, far-fetched simplifications in assuming the cross-sections' effective characteristics and negligence in calculating the global buckling led to disaster. It was not the only case, though. Similar failures known from press reports [12] and [13] occurred in Slovakia (fig. 5a, 5b), and Russia [14], where roofs of sports facilities collapsed in winter conditions (fig. 4b).

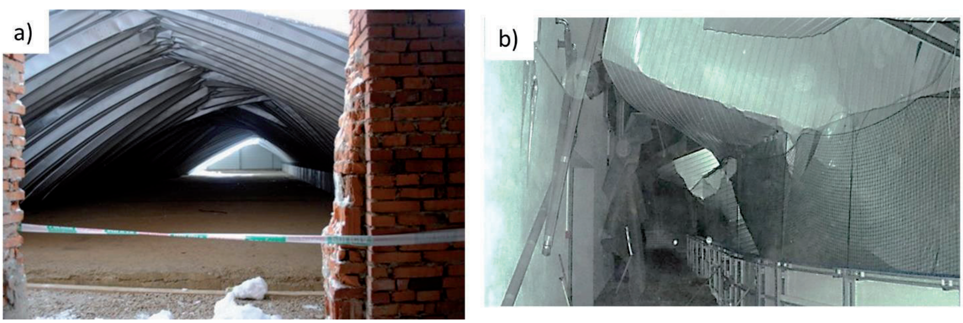

Fig. 5 Collapse of the hall roof, a) Stara Ľubovna (Slovakia) [12], b) Trstená (Slovakia) [13]

The abovementioned incidents raise justified doubts as to the validity of previously used engineering methods of designing. In paper [11] as well as in other relevant studies [15], [16] and [17] the authors indicated the need to take into account the specificity of K-span profiles in designing by using appropriate research and computational methods. It became clear that neglecting the transverse corrugation of the profiles entails the risk of wrong assessment of the load capacity and stability of K-span structures.

This paper presents a review of different research and analytical concepts (including the authors' own concepts) concerning the approach to solving the problem of load capacity and stability of K-span double corrugated structures. The purpose of the paper is to discuss selected research and analytical papers, which (according to the authors of this paper) contributed to the dissemination of analyses of K-span system double corrugated arch structures. The paper also includes conceptual and problematic areas pertaining to the analysis of the issues of load capacity and stability of double corrugated arch structures, which were previously neglected or have not been solved.

2. Development of experimental methods

Studies on double corrugated arch structures presented in previous publications and technical reports are proprietary solutions, which mainly result from immediate design needs. The materials are often dispersed and incomplete and, as such, it is difficult to determine cohesive and systematic test methods. A section of this paper presents selected studies, which have made a significant contribution to the development of the methods of double corrugated arch structure testing.

The first extensive paper concerning the analysis of load capacity and stability of double corrugated arch structures was published in 1974 by H. Mang. It was a doctoral thesis [4] on the static and dynamic analysis of arch structures according to the finite elements method, including a proposal of experimental tests. In 1976, the same author published the results of his work in paper [5]. The paper was devoted to developing the rules of constructing a computational model based on the finite elements method. Similar to the thesis, it concerned static and dynamic computational methods, including an experimental verification. The theoretical assumptions of H. Mang's works were accurate and useful, but unfortunately also complicated and difficult to use in practice. The computational rules defined for the finite elements method exceeded the capacity of numerical computational methods of that time. Perhaps this is why no follow-up on a wider scale should be expected.

In his studies, H. Mang analysed a double corrugated U section, whose shape significantly deviates from the contemporary K-span systems (ABM 120, ABM 240) described in Section 2. Nowadays, U sections are no longer used, which significantly reduces the universal character of the results of the presented analyses.

Further research on the load capacity and stability of double corrugated profiles was carried out by S. Sweeney et al. [18]. This was the first paper which used the K-span name to describe Rapid Erectable Lightweight Mobilization Structure (RELMS) technology, commonly used in the 1990s in the US Army Corps of Engineers. The research concerned a system which corresponded to the contemporary

ABM 120. The research schedule included checking the load capacity of a set of profiles, which was applied to three independent models:

a) in a supporting beam system with a 1.2 m extension, bent in two loading directions,
b) in a single-span beam system with a 18.3 m freely supported at loading with a couple of forces with 1/3 spacing of the span in two loading directions,
c) full-size arch with 15.2 m span and 5.5 m in height, loaded with force concentrated in the middle of the span and loaded in one direction, i.e. pressing to the ground.

The purpose of the study was to identify the maximum positive and negative bending moments in each of the three abovementioned research models. It was ultimately determined that the highest values of the bending moments (in reference to the positive moment) occur in the design with supports. In the beam design, a load capacity drop by ca. 13% was observed, while in a full-arch design the load capacity decrease was as high as 40% compared to the design with supports. Report [18] mentions a very important piece of information, namely that corrugation of a K-span profile contributes to differentiation of the acceptable positive bending moments in reference to the negative ones by ca. 20%. The profile revealed very strong non-linearity and is clearly prone to local loss of stability in the corrugation area. The support and beam model were examined with no impact of lengthwise forces, whose participation in arch structures is significant. That is why such a significant decrease in load capacity was observed in the arch design examination. The K-span arch structure analysed in report [18] finally received positive recommendations of the research team as useful for building purposes.

A report by D. Briassoulis et al. [19] refers to computational methods and was most probably developed simultaneously or at the early stages of research [18], because it refers to the same research results in its comparative section. The computational method presented in [19] is an original approach in which computational methods using the concept of a bar super element with orthotropic characteristics was first proposed, which takes into account the transverse corrugation of the profile. The paper describes a number of rules concerning computational methods (e.g. orthotropic reduction coefficients) and guidelines pertaining to geometrical non-linearities and local instabilities. Besides theoretical assumptions, the paper presents practical results of calculations and specifies the acceptable loads for arch structures.

It is worth emphasising that papers [18] and [19] were devoted to the support conditions of arch structures at full restraint. This confirms the usefulness of testing the aforementioned support design. In fact, the original mounting documentation assumes pouring concrete in the free arch edges of the foundation blocks. This was confirmed in K.L. Roye's documentation [20], which clearly includes it in the mounting process description. Although the documentation [20] applied to another K-span system, i.e. ABM 240 profile, in the 1990s it was a common method of mounting these systems.

Nowadays, restraining the free edges in the foundation blocks is no longer used. The present solution is based on screwed connections arranged in several rows on the corrugated web, which enables mounting to the steel ground beam. Such a connection looks like an articulated support rather than a restraint. It changes completely the distribution of internal forces in the arch's static design. It also means that archival documentations [18] and [20] have very limited practical value and their use is not recommended.

Tests on samples in a beam arrangement, described in a paper by M.J. Yagodich [21], were designed in a similar way as described before. The tests were carried out on profiles which resembled the contemporary ABM 240 system. The tests were performed on semi-finished profiles, i.e. without corrugation and with full corrugation, curved to form a circular arch. Despite lack of quantitative presentation of the test results, the authors emphasised the non-linear character of the test samples strain, attributing it to local instability related to corrugation of the web surface. The study entailed a number of numerical analyses using cover designs in order to validate the numerical model. The main purpose of the analyses was to identify the material model whose use in the numerical model would enable the obtaining of calculation results as close to the test results as possible.

Tests on a small beam model (1.6 m span) were presented in a paper by D. Zhadanov et al. [22]. The study used a different loading method than previous models. Instead of loading with a couple of focused forces, a surface load exerted by a set of weights was applied. The load was applied separately to the top (flanges) and bottom (web) part of the section. As revealed by the test results, the load application method affects the deflection and load capacity characteristics. When the load is applied to the web, the sample deflection is smaller than when the same load value is applied to the flanges. At the top load, the load–deflection characteristics are practically linear, while for the bottom load the characteristics are clearly curved. According to the authors of the paper, this is related to unfavourable stress distribution on the profile wall surfaces at the bottom load. The summary presents conclusions, which state that the flexural rigidity of the profile changes as the load increases.

An original research approach is presented in a paper by E. Ariumyan et al. [23]. It describes field studies carried out on full-scale K-span structures with the following arch dimensions (span/rise): 16.6 m/5.2 m, 18 m/6.6 m and 21 m/7.1 m. The originality of the solutions is based on using loads which represent symmetrical and non-symmetrical snow deposition on the roof for two models with 21 m and 18 m spans. The load was applied with a set of slings with reflex configuration, which enabled maintaining constant loads in the place where forces applied at the arch geometry changed during loading. In the case of the 16.6 m arch span, a point and rope load was used. Despite a limited number of results presented in the paper, the non-linear character of the structure operation was confirmed. It was also observed that at a certain load range, the arch structure gains a non-symmetrical secondary configuration of the balance position. This can be most probably attributed to the formation of local plastic joints and the redistribution of internal forces along the arch length. Similarly to previous papers, this one also included numerical calculations. The authors used a non-linear analysis and a bar model whose moment of inertia was reduced by the previously identified coefficients. Unfortunately, the method of determining the coefficients was not presented in detail.

Besides tests on full-scale arch structures or their parts, studies were carried out to evaluate local instability on small samples compressed axially and eccentrically. The paper by L-L. Wu et al. [24] was among the first devoted to this issue. Tests were conducted on small profile samples 0.6 m long, which were subject to axial and eccentric compression. Numerical analyses were performed simultaneously, aimed to compare the test results and to evaluate to what extent the theoretical assumptions used for building the numerical model refer to the actual response of the structure to variable loads. Based on the test results, it was identified that as compressive force eccentricity increases, the profile load capacity decreases much faster than suggested by numerical analyses. The non-standard profile characteristics were attributed to the impact of the deep corrugation of the webs and geometry of the whole profile. Numerical analyses in this case included identification of the buckling form and acceptable stress. The paper presents the details of the numerical model development including optimisation of the Finite Elements mesh (FE) and the acquisition of a material model.

Studies concerning the profile corrugation influence on the profile load capacity are comprehensively presented in a paper by L. Xu et al. [25]. Curved corrugated profiles and straight non-corrugated ones were subject to axial compression tests. These revealed that curved (corrugated) profiles have much lower load capacity than straight (non-corrugated) ones, and the character of local destruction in both profiles differs significantly. A non-standard test was performed, which included compressing samples cut out from the whole profile, taken from bent corners and corrugate profile flanges. The local influence of corrugation at the corner and flange bends was evaluated. The tests of corner sections revealed a tendency towards local collapse in the corrugation area, while profile flange sections demonstrated torsional loss of stability. This means that the destruction mechanism is initiated in the corrugated corners and then leads to loss of cross-corrugated web stability. The section flanges are least susceptible to local loss of stability, which was confirmed by studies on a full curved profile section.

Besides the previously described research works and FE analyses, studies were carried out on a theoretical model of a bar super element (J. Zaraś et al. [26]). The paper presents theoretical fundamentals and a computational example using orthotropic bar elements. A certain practical difficulty results from the complexity of theoretical theses and the lack of confirmation by research. Nonetheless, this is an interesting proposal for solving the problems of load capacity and rigidity of double corrugated arch structures, and perhaps further research will take place.

The research and analytical studies presented in this paper only form part of the publications devoted to the subject matter. The selection of publications was aimed at presenting a review of the development directions of previous works on the stability and load capacity of double corrugated arch structures. The aforementioned archival papers were focused on the relationship between tests on experimental elements in natural scale and parts of structures, as well as on the development of computational methods. The inadequacy of measurement methods in research is challenging. It was shown that point measurements can be useful only for the total evaluation of critical load capacity and the stability of structures, while the characteristics related to the limit of load capacity and the development of local instabilities were difficult to analyse with the measurement techniques available at the time. This inconvenience was amended with proposals of calculations, including numerical analyses. The development trend of experimental studies and computational analyses inspired further works.

3. Contemporary concept of studies and analyses

The differentiation between research works with historical significance and contemporary studies concerning analyses of double corrugated arch structures results mainly from the emergence of new technical possibilities of modern measurement systems, as well as the availability and efficiency of numerical computational methods.

In their paper, A. Piekarczuk et al. [27] presented the results of studies and analyses of a full-scale test structure in the form of a circular arch (Fig. 6a). The structure consisted of four TG system profiles with a section as presented in Fig. 6b, made of 1.25 mm thick steel sheet. The test sample had a span of 12.0 m, 6.0 m high and width 2.4 m (Fig. 7, a, b). The loading system was composed of coupled, reflex beams (similarly to paper [23]), which enabled the obtaining of 16 concentrated forces arranged over the arch surface (Fig. 7c). A substitute load with concentrated forces represented uniform snow load according to [28]. Tests were performed in a laboratory using two measurement systems, i.e. a standard one with displacement detectors and extensometers, and a Digital Image Correlation (DIC) optical system [29] and [30], which was first used for the measurement of large arch structures. DIC is a method of displacement and strain measurement used in experimental mechanics [31], which is characterised by contactless measurement, scalability of sensitivity and scalability of the measurement field dimensions. Since its development, i.e. the 1980s [32], the method has been subject to a number of changes and modifications, which improved its accuracy and measurement efficiency [33], [34], [35], [36], [37], [38], [39], [40] and [41], as well as helped to adapt it to new applications [42], [43], [44] and [45].

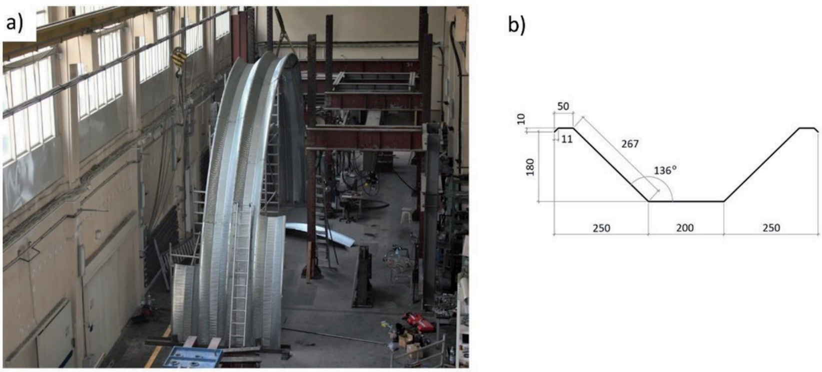

Fig. 6. Test item, a) mounting of segments, b) profile cross-section, dimensions in [mm]

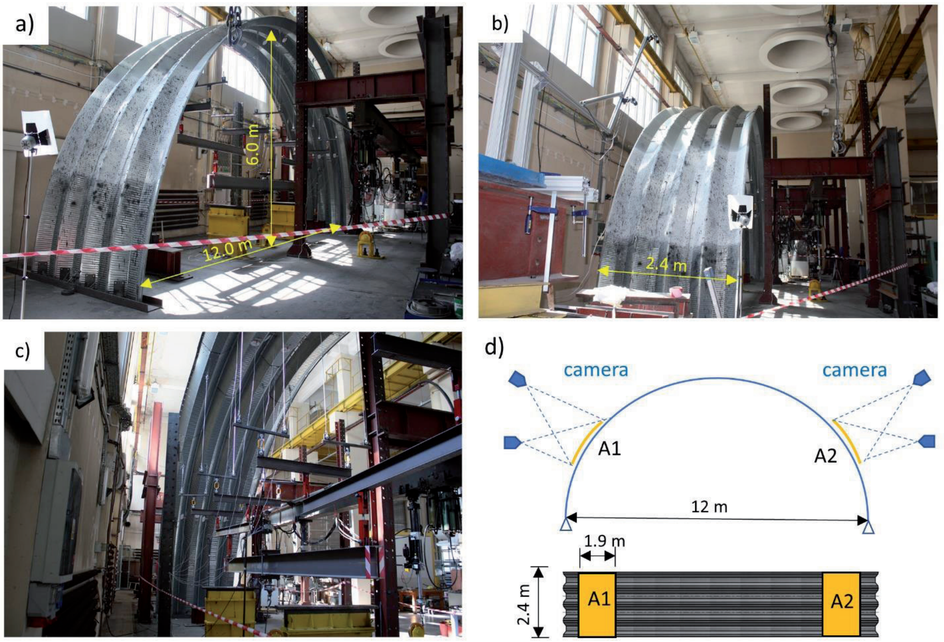

Fig. 7. Test item 12.0 × 6.0 m, a) sample dimensions – span, high, b) sample dimensions – width, c) load system, b) DIC measurement fields and camera sections

The DIC measurement system covered two surface observation fields (dimensions 2.4 × 1.9 m each – fig. 7 d) arranged symmetrically on both sides of the arch in places where the greatest strain of the structure was expected. Spot displacement sensors and extensometers were arranged in the DIC observation fields and on the arch apex. A standard measurement system was used for checking displacement and strain in the reference measurement points and for verifying the correctness of the DIC optic system measurements. Consequently, a very good correlation of the results of displacement measurements was obtained for both systems, with an error not exceeding 2%.

Besides comparison of the results with two different methods, FEM (Finite Method Element) numerical methods were used to evaluate the structure, which consequently helped to develop a hybrid method of FEM-DIC analysis, which laid the ground for the development of non-linear hybrid computational methods using numerical procedures.

Paper [46] presents studies on K-span double corrugated arch structures with load and measurement system similar to the article [27]. An arch test piece with a 12.0 m span, 2.3 m high and 2.4 m width was the test object (Fig 8 a, b). The model consisted of four profiles, as shown cross-section in Fig. 2a. A significant modification of the measurement method was implemented by using a wider measurement field in the DIC. It was assumed that four partly overlapping measurement fields are observed (Fig. 8 c, d)), which enabled obtaining data from all fields.

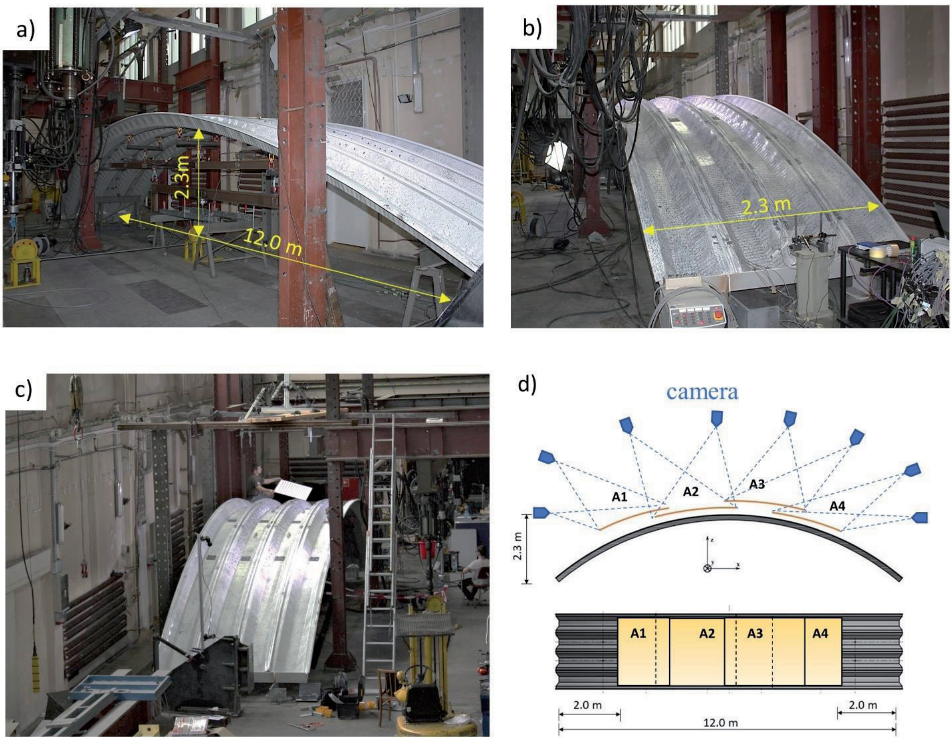

Fig. 8. Test item 12.0 × 2.3m, a) sample dimensions – span, high, b) sample dimensions – width, c) DIC system calibration, d) DIC measurement fields and camera sections

The measurement data (displacement, strain) collected during the studies enabled an analysis of the test piece's stability and load capacity in the full scope of static operation until the piece was destroyed. The test results helped to collect a significant amount of data, which were further used to verify the numerical model.

Besides load capacity and stability tests on double corrugated arch structures, paper [46] presents a comprehensive method of numerical model construction and analysis. This part of the study was oriented towards testing computational procedures in order to identify an optimum numerical task solution. The obtained calculation results correlated with the test results. The analysis checked the numerical model correctness and verified the assumptions made for the calculations. Finally, optimum computational procedures were indicated, alongside an extensive commentary concerning their validity. The main idea behind such measures was to develop principles for the construction and analysis of a numerical model in such a way that it could be used in the future for the analysis of an arch structure made of double corrugated steel sheets, with no need to perform complicated and time-consuming laboratory tests.

Tests on full-scale structures were also the subject of studies presented in the paper by X.P. Wang et al. [47]. In this case, arch structures made of three profiles, whose shapes and dimensions corresponded to the ABM 240 system (Fig. 2), were tested. The tested pieces had the span/rise of: 18/4.5 m and 30/7.5 m. Two types of loads were used, i.e. symmetrical and non-symmetrical. The loading system was completely different than the one presented in papers [23], [27] and [46]. Instead of compressed loading systems, independent gravitational loads were applied, distributed in several points on the structure surface. Each load point was controlled separately by adding weights. Displacement was measured with geodetic methods. Paper [47] describes comparative numerical calculations. An interesting aspect of the calculations is that numerical models were assumed, with orthotropic characteristics of the profile cross-section walls, which should represent structural and material non-uniformity of the corrugated profile parts. An analytical approach method concerning the identification of the characteristics of orthotropic profile parts was presented in a paper by L.T. Sun et al. [48] in reference to studies [47] and previous studies carried out by X.P. Wang et al. [47] A similar approach was described in paper [26] but instead of searching the orthotropy of the section walls, a concept of bar super element with orthotropic characteristics was used.

Besides tests on full-scale arch structures, tests in a much smaller scale were also performed. They included a part of a single profile with small dimensions (up to 1.0 m), which was isolated (cut out) from the complete structure. A test sample prepared this way had the actual geometrical features (shape, dimensions, corrugation) but required the use of appropriate supports, which helped to maintain proper boundary conditions. The test samples were subject to axial and eccentric compression.

The concept of such tests was originally presented in the paper by L-L. Wu et al. [24]. The method was highly recognised in the scientific community and subsequent studies developed the research method and enriched it with contemporary measurement techniques.

Studies presented in papers by A. Piekarczuk et al. [16], [49], [50] and [51] included tests on a small part of a profile. Similarly to the studies by L-L. Wu et al. [24] and [52], the purpose was to identify the mechanism of local instability development and the numerical analyses used to represent the phenomena. The reference studies used a completely different method of loading the test sample than previous works [24] and [52]. The innovative aspect of the method was based on an original way of loading and measuring the displacement and strain with the DIC technique (Fig. 9). The test device enabled eccentric loading in a wide range of eccentricity adjustment of ± 200 mm. Besides the compressive force measurement, it was also possible to measure the angles of the test sample supports rotation. Apart from standard data acquisition systems based on displacement sensors, a contactless DIC optic method was used, which was the same as in the description of full-size structure tests. It helped to obtain 3D measurement data from nearly the entire surface of the test sample. The results were employed in tests on different numerical models.

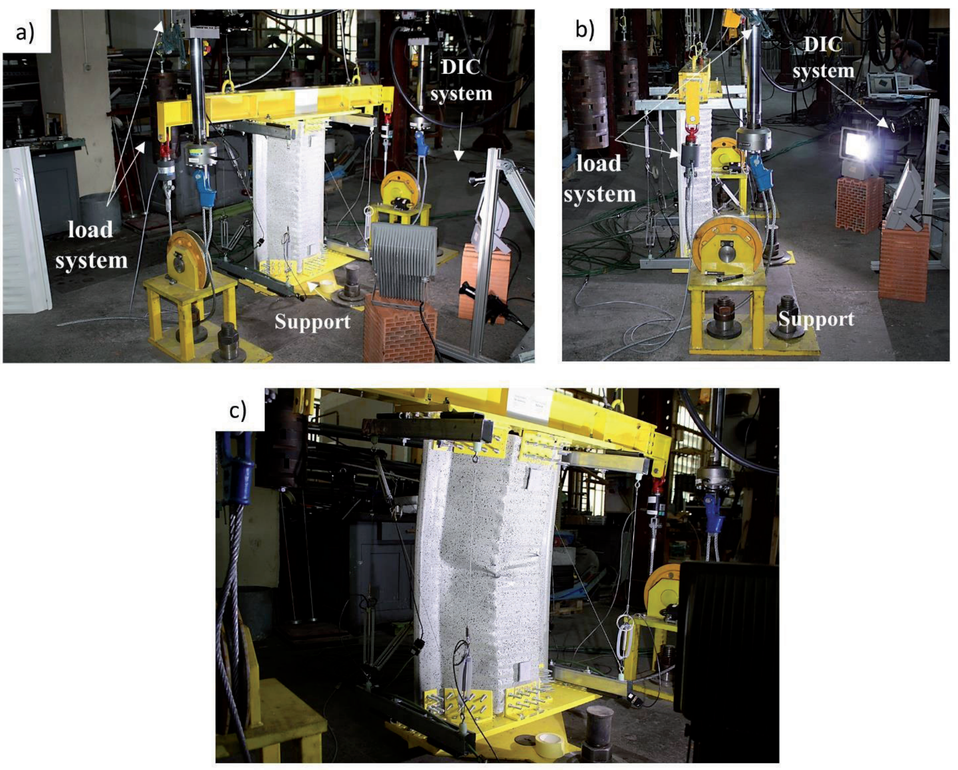

Fig. 9. Test setup of a single profile, a) load and measuring system (front view), b) load and measuring system (side view), c) sample after eccentric compression

It is worth mentioning that besides research, the study also included complex numerical analyses. A numerical model of a test piece obtained based on three-dimensional scanning was acquired for the numerical calculations. The accuracy of the model geometry obtained from 3D scanning is incomparably higher than the one based on traditional measurements. This is particularly important in the case of complex geometries such as K-span double corrugated profiles. Fig. 10 presents a comparison between scanned model, FE model based on design dimensions and real sample.

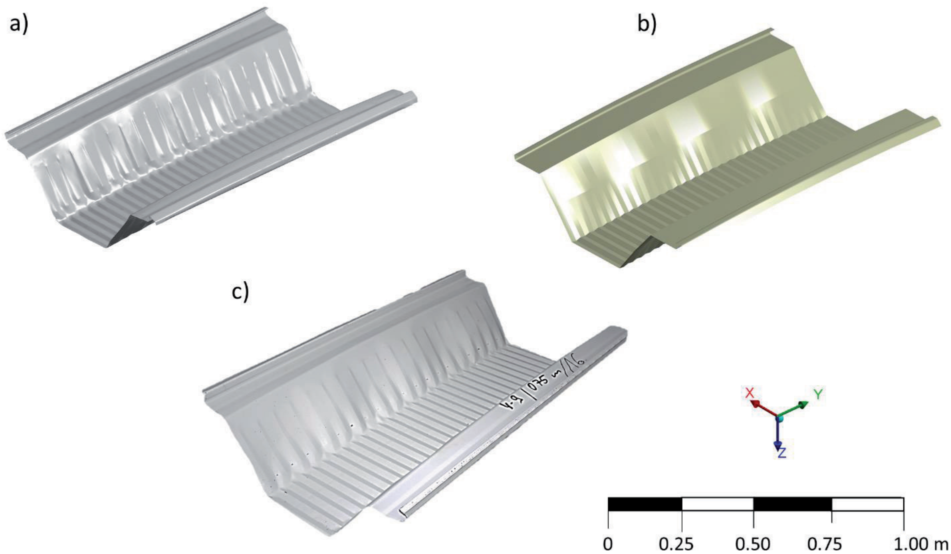

Fig. 10. Comparison of the geometry of numerical models, a) 3D scan, b) graphical model ANSYS, c) real sample

Differences in geometry representation details are visible and do not require any further comment but the influence of geometry simplification on the calculation results, compared to the test results, is presented in detail in paper [50].

Studies and numerical analyses concerning the influence of cross corrugation on the load capacity and stability of K-span system double corrugated profiles were the subject of a paper by R. Cybulski et al. [52]. The tests were carried out on a small section of an ABM 120 profile (Fig. 3) according to a method similar to the one presented in paper [24]. The research described in the paper was innovative due to its scope. Two kinds of samples were tested, one of which was a K-span system semi-finished product (without transverse corrugation), while the other sample was double corrugated, i.e. after a complete rolling process. Complex numerical analyses of both models were performed, including the use of the profile geometry obtained by 3D scanning. The results were compared with the results of numerical calculations and calculations based on standards [7] and [9]. The results of calculations and tests confirmed that the standards [7] and [9] cannot be used to design the corrugated profiles.

Despite ABM 120 and ABM 240 K-span system pieces being different in their cross-section shape, transverse corrugation added during circular arch shaping contributed to the occurrence of similar local instability phenomena. Compared to profiles with flat walls and the same dimensions, transverse corrugation reduces the load capacity at bending from 15% to 30% and increases axial displacement at compression twice for comparable values of axial forces [16]. Similar conclusions concerning axial displacement at comparable forces were discovered in paper [52].

Extensive studies devoted to the load capacity and stability of arch structures made of double corrugated steel sheets are presented in the PhD thesis of R. Cybulski [53], and the MSc theses of R.S. Crespo [54] and A. Piekarczuk [55].

4. Further concepts of computational and experimental methods development

The issues discussed in Sections 2 and 3 present selected examples of experimental methods development and, in some cases, their contemporary follow-up. It does not, however, exhaust the need for further development of double corrugated arch structure evaluation methods. Contemporary experimental studies and numerical analyses encounter a number of issues which have not been analysed before. The status of current knowledge can be attributed to the difficulty in using previous measurement and analytical techniques. This section of the paper presents potential directions of the concept development, which could supplement previous experimental and computational methods.

Full-scale arch structure tests are carried out for different support methods. At present, arch structures are fixed to steel or reinforced concrete beams with bolts and anchors that are usually located in the middle of the profile. In reference to the static operation principles of a structure, such a fixing method is an intermediate solution between restraint and articular support. Elastic supports are the most appropriate kind of support in this case. Unfortunately, no tests specifying the characteristics of an elastic support in reference to double corrugated structures have been carried out, but a number of analyses have been performed which could be useful for identifying the impact of an arch structure's elastic support on its stability and load capacity. The authors of paper [56] checked the impact of vertical and horizontal supports elasticity on its stability and load capacity. The analyses revealed that for most elastic supports the buckling load is lower, and the buckling forms change. Paper [57] describes an analysis of the impact of elastic rotational end-restraints on the non-linear behaviour of an arch structure. Interesting solutions were obtained, useful for making the computational methods more precise. Besides an analysis of arch structures' stability, the authors of paper [58] also demonstrated a significant impact of the elastic support of arches on the change in internal forces arrangement (axial force, bending moment), compared to structures with no elastic support. Similar analysis results were presented in papers [59] and [60], which conclusively describe the significant effect of support elasticity on the load capacity and stability of structures. Another interesting scientific issue is related to the influence of symmetric and asymmetric elastic supports on the non-linear equilibria and buckling responses of arches [61]. It was identified that the stiffness of symmetric elastic supports greatly affects the bifurcation loads of secondary paths with asymmetric configurations.

Despite reference to various cross-sections of arch structures, the analysis method presented in the aforementioned papers can also be useful for double corrugated arches. Certainly, there are some qualitative and quantitative differences, especially in terms of defining the support elasticity. The idea and need to carry out such analyses are essential as they contribute to a change in the computational approach.

Accurate analysis methods concerning local and overall interactive buckling are a permanent problem in arch structure evaluation. The authors of the paper, X. Gao et al. [62], examined the influence of corrugation on local buckling formation in arch structures. Based on analyses, it was discovered that the mechanism of local instability formation depends on the profile shape and dimensions.

Another interesting issue is related to taking geometrical imperfections into account in computational analyses [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73]. The shell structure sensitivity to geometrical imperfections was the subject of a paper by J. Sorić [74]. Based on numerical analyses, it was discovered that imperfections within a certain amplitude range (1/10 of the coat thickness for the first buckling form) has a minor impact on structure stability and load capacity change, compared to the results obtained for a perfect structure. It must be emphasised that the analyses were carried out for a non-corrugated surface. The authors' own studies included similar influence analyses [46] but they concerned double corrugated arch structures. The influence of imperfections with the same amplitude and, interestingly enough, no significant influence on the stability change, were observed compared to a model without imperfections. The reference studies tested only one imperfection type and size for a single structure and load. In order to evaluate fully the influence of imperfections on the load capacity and stability of structures, including arch ones, further works should be carried out as presented by Z. Lu et al. [75]. The paper describes tests on different imperfections at three variable parameters (two related to structure geometry and one to material properties). The results of the analysis reveal that at relevant parameters of imperfection and yield points thin shells (covers) are more efficient from a construction point of view than thick ones. The influence of imperfection on the arch structure load capacity and stability was also investigated in paper [76], where a complex numerical element was used for evaluating the sensitivity of arch structures to geometrical imperfections. Paper [77] analysed non-linear cases of arch stability with a special consideration for geometrical imperfections, similarly to papers [78] and [79]. For complex matters concerning the interaction of local and global instabilities, it seems reasonable to use innovative analyses such as the Generalised Beam Theory (GBT) presented in papers [80], [81] and [82]. Although the papers apply to frame structures, the presented methods can be highly efficient in an arch structure analysis.

Other important issues which should be developed in the analysis of double corrugated arch structures include elastic buckling, non-linear buckling and post-buckling behaviour. The foundations of analytical deliberations on the issues are presented in papers [83], [84], [85], [86], [87], [88], [89] and [90]. Contemporary follow-up on their ideas is presented in paper [91], which applies to the testing of non-linear elastic in-plane buckling and post-buckling parabolic arches in reference to analytical numerical solutions. A similar issue was presented in [92] where non-linear elastic buckling and post-buckling of pin-ended parabolic multi-span continuous arches were analyzed.

As mentioned in the paper, analytical solutions suffer from limitations which have not been identified previously. Paper [93] analysed numerical calculation methods of non-linear issues. Detailed numerical tests obtained a high degree of accuracy of buckling analysis, especially in the bifurcation critical point. Similar issues were analysed in paper [94]. The authors focused on buckling and post-buckling analysis using an asymptotic-numerical method for the improvement of the effectiveness and efficiency of numerical calculation methods. Further development of numerical methods in the analyses of elastic post-buckling behaviour and imperfection sensitivity of cylindrical steel is described in paper [95]. In this case, the possibility of using the original GBT method (mentioned earlier in papers [80] and [81]) was taken into consideration in order to clarify the standard mechanics of finite elements. Paper [96] applies to the non-linear buckling of circular arches including shear deformation, as well as under various loading and support conditions. In this case, analytical solutions are compared with the results of numerical calculations.

The stability of arch structures was the subject of papers by M.A. Bradford et al. [97], [98] and [99]. The authors made a very interesting observation concerning the pre-buckling deformation effect. The issue has been neglected in classical buckling theory but it affects stability, especially in the case of shallow arches at distributed and concentrated loads. Paper [100] applied to the methods of solving non-linear stability behaviour, including pre-buckling and buckling configurations, in reference to circular shallow arches. The paper presents a comprehensive approach to non-linear stability analysis and bifurcation-type buckling. A paper by Sun-ting Yan et al. [101] is devoted to the stability of arch structures, taking into account the different stiffness of structures and different support conditions. It is a special approach to structure analysis because it accounts for the occurrence of different degrees of stiffness in the same structure. Such an approach can be useful for the analysis of double corrugated arch structures because our own analyses have revealed that the stiffness of a K-span profile can be subject to significant changes as effort increases.

Besides analytical and experimental approaches, numerical calculation methods are an important scientific area in the analysis of thin-walled structures. There is a number of papers dedicated to shell-type structures, e.g. [102], [103], [104], [105], [106], [107], [108] and [109]. The papers discuss FEM implementation for special applications in thin-walled structures. Besides the way in which the finite elements method is used, usability in the context of error identification is an important issue. An interesting approach to the analysis of errors resulting from the use of non-linear numerical calculation methods is described in paper [110]. It presents the main areas of occurrence of errors, which are critical for numerical analysis.

It is worth pointing out that despite scientific activity and the extension of knowledge in the field, these issues still require further studies and analyses, especially in relation to double corrugated steel sheet structures.

The issues are strongly related to the profiles' cross-section, as well as the arch structure dimensions and load type, and are important in light of the scientific development of accurate methods of analysis, especially in reference to double corrugated arch structures. The shape of a double corrugated arch structure after rolling deviates significantly from typical cold-rolled profiles because its surface contains ribs and waves. Such a shape of the profile surface prevents the use of the typical design methods presented in the aforementioned standards [7], [8], [9] and [10], and makes it difficult to use scientific methods to analyse the local instabilities of profile flat areas [111], [112] and [113].

Another important scientific concern is the inclusion in the calculations of the changes in the material structure and mechanical properties in reference to residual stress phenomena. The need to include these phenomena in the analyses of double corrugated structures was analysed in papers [46], [114] and [78]. As mentioned in Section 1, double corrugated profiles are formed as a result of two-stage cold rolling. In the first stage, the tray shape is formed, followed by cross rolling of a straight profile section, which results in the formation of a circular shape towards the profile's longitudinal axis.

During cold rolling, transverse ribs and waves are formed on the profile wall surface. In the case of steel sheets, this leads to permanent plastic strain, and such parameters as yield point, tensile strength elongation can change compared to the original characteristics of the steel before rolling. Generally, it can be concluded that individual parts of a rolled section can be subject to various degrees of permanent or temporary plastic strain. Consequently, different mechanical properties of the material are obtained in different parts of the same section. The first studies concerning the identification of the steel mechanical properties in double corrugated profiles were presented in papers by A. Piekarczuk et al. [50] and R. Cybulski et al. [52]. The authors conducted pilot tests on a small number of samples, which yielded a complete qualitative and quantitative evaluation of the phenomenon. It seems valid to carry out future studies on residual stress in double corrugated arch structures and to support them with theoretical maxims and research methods described in papers: [115], [116], [117], [118], [119], [120], [121], [122], [123], [124], [125], [126] and [127], as well as in textbooks [128] and [129].

5. Summary

The K-span system has been available in the global construction market for nearly eighty years. The system is well rooted in the history of civil engineering and is an engineering solution still used and developed. A structure, which appeared to be basic and was originally considered as temporary, has gradually become more popular and permanent and has been the subject to many modifications in many parts of the world. The very concept of the Quonset Hut, currently known as K-span, has not changed for many years. The system was supposed to be safe, cheap and easy to mount. The advantages of the structure are related to its simple production and mounting, as well as functional value.

Despite the rich history of double corrugated arch structures manufacturing and application methods, designing such structures can still be problematic. The consequences of such knowledge can be serious due to the potential occurrence of failures or disasters. That is why research on such arches should continue, especially because currently there are no design standards valid for double corrugated arch structures.

This paper presents a review of selected studies and a description of the current state of research in the context of the development of experimental and analytical methods. It is worth emphasising that the majority of the papers were developed in different periods of time, in independent research centres. Despite the difficulty in defining cohesive rules of analysing such structures, the tendency to develop experimental and computational methods is clear.

According to the authors of the paper, further development of analytical works will mainly focus on the improvement of computational methods, especially concerning elastic buckling, non-linear buckling and post-buckling behaviour, including the influence of material processing on residual stress. Most probably, the analyses will be carried out using numerical computational methods based on the finite elements method or experimental and numerical hybrid methods. New measurement solutions and Digital Image Correlation methods used for large structure measurements play a particularly important role nowadays for the development of experimental studies. These methods provide incomparably greater measurement capabilities than traditional methods, which contributes directly to the accuracy and quality of the obtained test results.

The literature review of the latest developments presented in the paper summarises the authors' knowledge of the field. The paper attempts to forecast future directions of double corrugated arch structures research and analysis development. The authors of the paper work towards the improvement of experimental and analytical methods.

References

[1] J. Decker, C. Chiei, Quonset Hut, Princeton Archit.Press, New York, NY, 2005. https://doi.org/10.1007/1-56898-654-8
[2] J.S. Garnetr, World War II Temporary Military Buildings: A Brief History of the Architecture and Planning of Cantonments and Training Stations in the United States., Virginia, 1993
[3] K.L. Draper, Wartime Huts: The Development, Typology and Identification of Temporary Military Buildings in Britain 1914-1945, University of Cambridge, 2017
[4] H.A. Mang, Analysis of Double Corrugated Shell Structures by the Finite Element Method, Texas Tech University, 1974
[5] H.A. Mang, “Finite element analysis of doubly corrugated shells” , *Journal of the Structural Division*, no. 102, pp.2033–2051, 1976. http://cedb.asce.org/CEDBsearch/record.jsp?dockey=0006980 (accessed January 24, 2018)
[6] J.B. Richman, “K-span-consulting” n.d. http://k-span-consulting.com (accessed March 28, 2017)
[7] European Committee for Standardisation, EN 1993-1-1: Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings, 2005
[8] European Committee for Standardisation, EN 1993-1-3: Eurocode 3: Design of steel structures - Part 1-3: General rules - Supplementary rules for cold-formed members and sheeting, 2006
[9] European Committee for Standardisation, EN 1993-1-5: Eurocode 3: Design of steel structures - Part 1-5: General rules - Plated structural elements, 2006
[10] European Committee for Standardisation, EN 1993-1-6: Eurocode 3: Design of steel structures - Part 1-6: Strength and stability of shell structures, 2007
[11] A. Biegus, A. Kowal, “Collapse of halls made from cold-formed steel sheets” , *Engineering Failure Analysis*, no. 31, pp.189–194, Jul. 2013. https://doi.org/10.1016/j.engfailanal.2012.12.009
[12] P. Rindos, “V Starej Ľubovni sa zrútila strecha zimného štadióna” , *Denník SME*, n.d. https://spis.korzar.sme.sk/c/6696874/v-starej-lubovni-sa-zrutila-strecha-zimneho-stadiona.html (accessed December 8, 2017)
[13] J. Pustayová, “Spadnutá strecha štadióna: Príčina je už známa” , *PLUS Jeden Deň*, n.d. http://www.pluska.sk/regiony/stredne-slovensko/spadnuta-strecha-stadiona-pricina-je-znama.html (accessed December 8, 2017)
[14] А. Загуменская, “Руководство парка Южно-Сахалинска ищет причины обрушения крыши ангара (in Russian)” , *Губернские Ведомости*, 2018. https://skr.su/news/post/105972/ (accessed November 24, 2020)
[15] V. Amghel, S. Sorohan, N. Constatnin, I. Stolica, On the analysis on a cold formed steel profile arch structure,

in: Acta Electroteh., 2016
[16] A. Piekarczuk, "Test-supported numerical analysis for evaluation of the load capacity of thin-walled corrugated profiles" , *Bulletin of the Polish Academy of Sciences Technical Sciences*, no. 65, Jan. 2017. https://doi.org/10.1515/bpasts-2017-0087
[17] R. Walentyński, R. Cybulski, K.J. Kozieł, Achilles' heel of the ABM 120 double corrugated profiles, in: New Trends Statics Dyn. Build. Slovakia Univ. Technol. Bratislava, Faculty of Civil Engineering STU Bratislava Slovak Society of Mechanics SA, 2011: pp. 25–28
[18] S. Sweeney, D. Briassoulis, A. Kao, AD-A231 699. Evaluation of K-Span as a Rapidly Erectable Lightweight Mobilization Structure (RELMS), 1991. http://www.dtic.mil/docs/citations/ADA231699 (accessed July 10, 2018)
[19] D. Briassoulis, A. Kao, S. Sweeney, AD-A187 716. Determination of the Ultimate Loads for Corrugated-Steel, Barrel-Type Shell Structures., 1987. http://www.dtic.mil/docs/citations/ADA187716 (accessed July 10, 2018)
[20] K.L. Roye, Metal building construction using the MIC-240 ABM K-Span machine, Monterey, California, USA, 1996. http://www.dtic.mil/docs/citations/ADA322031 (accessed July 10, 2018)
[21] M.J. Yagodich, Numerical Evaluation of Thin-Shelled Structural Panels - D-Scholarship@Pitt, University of Pittsburgh, 2003. http://d-scholarship.pitt.edu/6977/ (accessed April 10, 2018)
[22] D. Zhadanov, V. Ulascvich, I. Zinkevich, "Experimental Testing of an Arched Roofing Panel Made of MIC-120 Thin-walled Cold-formed Steel Profiles with Transverse Corrugations " , *СТРОИТЕЛЬСТВО. ПРИКЛАДНЫЕ НАУКИ. Строительные Конструкции*, pp.33–38, 2015
[23] E. Airumyan, O. Boyko, Full-Scale Testing and Design of Frameless Arch Steel Roof, in: K. Virdi, F. Raras, J. Clarke, G. Armer (Eds.), Struct. Assessment. Role Large Full Scale Test., E & FN Spon, 1997: pp. 211–217
[24] L. Wu, X. Gao, Y. Shi, Y. Wang, "Theoretical and experimental study on interactive local buckling of arch-shaped corrugated steel roof" , *Steel Structures*, no. 6, pp.45–54, 2006
[25] L. Xu, Y. Gong, P. Guo, "Compressive tests of cold-formed steel curved panels" , *Journal of Constructional Steel Research*, no. 57, pp.1249–1265, Dec. 2001. https://doi.org/10.1016/S0143-974X(01)00048-7
[26] J. Zaraś, K. (Katarzyna) Kowal-Michalska, J. Rhodes, A simplified Computation Model of Arch-Shaped Corrugated Shell Roof, in: Thin-Walled Struct. Adv. Dev. Third Int. Conf. Thin-Walled Struct., Elsevier, 2001: pp. 109–118
[27] A. Piekarczuk, M. Malesa, M. Kujawinska, K. Malowany, "Application of Hybrid FEM-DIC Method for Assessment of Low Cost Building Structures" , *Experimental Mechanics*, 2012. https://doi.org/10.1007/s11340-012-9616-2
[28] European Committee for Standardisation, EN 1991-1-3: Eurocode 1: Actions on structures - Part 1-3: General actions - Snow loads, 2003
[29] F. Chen, X. Chen, X. Xie, X. Feng, L. Yang, "Full-field 3D measurement using multi-camera digital image correlation system" , *Optics and Lasers in Engineering*, no. 51, pp.1044–1052, Sep. 2013. https://doi.org/10.1016/j.optlaseng.2013.03.001
[30] M. Malesa, K. Malowany, U. Tomczak, B. Siwek, M. Kujawińska, A. Siemińska-Lewandowska, "Application of 3D digital image correlation in maintenance and process control in industry" , *Computers in Industry*, no. 64, pp.1301–1315, Dec. 2013. https://doi.org/10.1016/j.compind.2013.03.012
[31] H. Schreier, J.-J. Orteu, M.A. Sutton, Image Correlation for Shape, Motion and Deformation Measurements, Springer US, Boston, MA, 2009. https://doi.org/10.1007/978-0-387-78747-3
[32] W.H. Peters, W.F. Ranson, "Digital Imaging Techniques In Experimental Stress Analysis" , *Optical Engineering*, no. 21, Jun. 1982. https://doi.org/10.1117/12.7972925
[33] B. Pan, "Bias error reduction of digital image correlation using Gaussian pre- fi ltering" , *Optics and Lasers in Engineering*, no. 51, pp.1–7, 2013. https://doi.org/10.1016/j.optlaseng.2013.04.009
[34] B. Pan, H. Xie, Z. Wang, K. Qian, Z. Wang, "Study on subset size selection in digital image correlation for speckle patterns." , *Optics Express*, no. 16, pp.7037–7048, 2008. https://doi.org/10.1364/OE.16.007037
[35] Y. Zhou, C. Sun, Y. Song, J. Chen, "Image pre-filtering for measurement error reduction in digital image correlation" , *Optics and Lasers in Engineering*, no. 65, pp.46–56, 2015. https://doi.org/10.1016/j.optlaseng.2014.04.018
[36] B. Pan, K. Li, W. Tong, "Fast, Robust and Accurate Digital Image Correlation Calculation Without Redundant Computations" , *Experimental Mechanics*, no. 53, pp.1277–1289, 2013. https://doi.org/10.1007/s11340-013-9717-6
[37] M.A. Sutton, J.H. Yan, V. Tiwari, H.W. Schreier, J.J. Orteu, "The effect of out-of-plane motion on 2D and 3D digital image correlation measurements" , *Optics and Lasers in Engineering*, no. 46, pp.746–757, Oct. 2008. https://doi.org/10.1016/j.optlaseng.2008.05.005
[38] H.W. Schreier, "Systematic errors in digital image correlation caused by intensity interpolation" , *Optical Engineering*, no. 39, pp.2915, Nov. 2000. https://doi.org/10.1117/1.1314593
[39] P. Lava, S. Cooreman, S. Coppieters, M. De Strycker, D. Debruyne, "Assessment of measuring errors in DIC

using deformation fields generated by plastic FEA” , *Optics and Lasers in Engineering*, no. 47, pp.747–753, Jul. 2009. https://doi.org/10.1016/j.optlaseng.2009.03.007

[40] M. Bornert, F. Brémand, P. Doumalin, J.C. Dupré, M. Fazzini, M. Grédiac, F. Hild, S. Mistou, J. Molimard, J.J. Orteu, L. Robert, Y. Surrel, P. Vacher, B. Wattrisse, “Assessment of digital image correlation measurement errors: Methodology and results” , *Experimental Mechanics*, no. 49, pp.353–370, 2009. https://doi.org/10.1007/s11340-008-9204-7

[41] R. Balcaen, L. Wittevrongel, P.L. Reu, P. Lava, D. Debruyne, “Stereo-DIC Calibration and Speckle Image Generator Based on FE Formulations” , *Experimental Mechanics*, no. 57, pp.703–718, Jun. 2017. https://doi.org/10.1007/s11340-017-0259-1

[42] Z. Tang, J. Liang, Z. Xiao, C. Guo, “Large deformation measurement scheme for 3D digital image correlation method” , *Optics and Lasers in Engineering*, no. 50, pp.122–130, Feb. 2012. https://doi.org/10.1016/j.optlaseng.2011.09.018

[43] M. Kujawinska, M. Malesa, K. Malowany, A. Piekarczuk, L. Tymińska-Widmer, P. Targowski, Digital image correlation method: a versatile tool for engineering and art structures investigations, in: R. Rodríguez-Vera, R. Díaz-Uribe (Eds.), 22nd Congr. Int. Comm. Opt. Light Dev. World, Aug. 2011: p. 80119R. https://doi.org/10.1117/12.915566

[44] M. Malesa, K. Malowany, J. Pawlicki, M. Kujawinska, P. Skrzypczak, A. Piekarczuk, T. Lusa, A. Zagorski, “Non-destructive testing of industrial structures with the use of multi-camera Digital Image Correlation method” , *Engineering Failure Analysis*, no. 69, pp.122–134, Nov. 2016. https://doi.org/10.1016/j.engfailanal.2016.02.002

[45] H.A. Bruck, S.R. McNeill, M.A. Sutton, W.H. Peters, “Digital image correlation using Newton-Raphson method of partial differential correction” , *Experimental Mechanics*, no. 29, pp.261–267, Sep. 1989. https://doi.org/10.1007/BF02321405

[46] A. Piekarczuk, “Experimental and numerical studies of double corrugated steel arch panels” , *Thin-Walled Structures*, no. 140, pp.60–73, Jul. 2019. https://doi.org/10.1016/j.tws.2019.03.032

[47] X.P. Wang, C.R. Jiang, G.Q. Li, S.Y. Wang, “Full-scale tests and finite element analysis of arched corrugated steel roof under static loads” , *Steel and Composite Structures*, no. 7, pp.339–354, Aug. 2007. https://doi.org/10.12989/scs.2007.7.4.339

[48] L.T. Sun, L.S. Lin, “Equivalent Analysis of Elastic Constants and Stability Calculation of Corrugated-Arch Metal Roof” , *Advanced Materials Research*, no. 542–543, pp.106–110, Jun. 2012. https://doi.org/10.4028/www.scientific.net/amr.542-543.106

[49] A. Piekarczuk, K. Malowany, P. Więch, M. Kujawińska, P. Sulik, “Stability and bearing capacity of arch-shaped corrugated shell elements: experimental and numerical study” , *Bulletin of the Polish Academy of Sciences Technical Sciences*, no. 63, pp.113–123, Jan. 2015. https://doi.org/10.1515/bpasts-2015-0013

[50] A. Piekarczuk, K. Malowany, “Comparative analysis of numerical models of arch-shaped steel sheet sections” , *Archives of Civil and Mechanical Engineering*, no. 16, pp.645–658, Sep. 2016. https://doi.org/10.1016/j.acme.2016.04.006

[51] A. Piekarczuk, P. Więch, R. Cybulski, “Experimental method to evaluate the load-carrying capacity of double corrugated sheet profiles” , *Thin-Walled Structures*, no. 144, pp.106283, Nov. 2019. https://doi.org/10.1016/j.tws.2019.106283

[52] R. Cybulski, R. Walentyński, M. Cybulska, “Local buckling of cold-formed elements used in arched building with geometrical imperfections” , *Journal of Constructional Steel Research*, no. 96, pp.1–13, May 2014. https://doi.org/10.1016/j.jcsr.2014.01.004

[53] R. Cybulski, Analysis of local stability of doubly corrugated thin-walled structures, Silesian University of Technology. Poland, 2015

[54] R.S. Crespo, Linear Stability Analysis of Double Corrugated 120 ABM Steel Arch Panels, Silesian University of Technology. Poland, 2012

[55] A. Piekarczuk, Experimental and computational evaluation methods of arch-shaped roof made of double corrugated shells (In Polish), Instytut Techniki Budowlanej, Warsaw, 2018

[56] Y.L. Pi, M.A. Bradford, F. Tin-Loi, “Nonlinear analysis and buckling of elastically supported circular shallow arches” , *International Journal of Solids and Structures*, no. 44, pp.2401–2425, Apr. 2007. https://doi.org/10.1016/j.ijsolstr.2006.07.011

[57] Y.L. Pi, M.A. Bradford, “Non-linear in-plane postbuckling of arches with rotational end restraints under uniform radial loading” , *International Journal of Non-Linear Mechanics*, no. 44, pp.975–989, Nov. 2009. https://doi.org/10.1016/j.ijnonlinmec.2009.07.003

[58] Y.-L. Pi, M.A. Bradford, “Lateral-Torsional Buckling Analysis of Arches Having In-Plane Rotational End Restraints under Uniform Radial Loading” , *Journal of Engineering Mechanics*, no. 139, pp.1602–1609, Nov. 2013. https://doi.org/10.1061/(asce)em.1943-7889.0000599

[59] Q. Han, Y. Cheng, Y. Lu, T. Li, P. Lu, “Nonlinear buckling analysis of shallow arches with elastic horizontal

supports" , *Thin-Walled Structures*, no. 109, pp.88–102, Dec. 2016. https://doi.org/10.1016/j.tws.2016.09.016

[60] Y. Lu, Y. Cheng, Q. Han, "Experimental investigation into the in-plane buckling and ultimate resistance of circular steel arches with elastic horizontal and rotational end restraints" , *Thin-Walled Structures*, no. 118, pp.164–180, Sep. 2017. https://doi.org/10.1016/J.TWS.2017.05.010

[61] Y. Zhou, Z. Yi, I. Stanciulescu, "Nonlinear Buckling and Postbuckling of Shallow Arches With Vertical Elastic Supports" , *Journal of Applied Mechanics*, no. 86, Jun. 2019. https://doi.org/10.1115/1.4042572

[62] X. Gao, L. Wu, H. Zhu, "Interactive local buckling analysis of corrugated plate assemblies of channel sections under uniform compression" , *Journal of Building Structures*, no. 26, pp.39–44, 2005

[63] L. Bruno, M. Sassone, F. Venuti, "Effects of the Equivalent Geometric Nodal Imperfections on the stability of single layer grid shells" , *Engineering Structures*, no. 112, pp.184–199, Apr. 2016. https://doi.org/10.1016/j.engstruct.2016.01.017

[64] J.L. Morais, F.M.A. Silva, "Influence of modal coupling and geometrical imperfections on the nonlinear buckling of cylindrical panels under static axial load" , *Engineering Structures*, no. 183, pp.816–829, Mar. 2019. https://doi.org/10.1016/j.engstruct.2018.12.032

[65] J. Shen, M.A. Wadee, "Sensitivity of elastic thin-walled rectangular hollow section struts to manufacturing tolerance level imperfections" , *Engineering Structures*, no. 170, pp.146–166, Sep. 2018. https://doi.org/10.1016/j.engstruct.2018.05.045

[66] X.Z. Cui, Y.G. Li, H.P. Hong, "Reliability of stability of single-layer latticed shells with spatially correlated initial geometric imperfection modeled using conditional autoregressive model" , *Engineering Structures*, no. 201, pp.109787, Dec. 2019. https://doi.org/10.1016/j.engstruct.2019.109787

[67] Z.L. Du, Z.X. Ding, Y.P. Liu, S.L. Chan, "Advanced flexibility-based beam-column element allowing for shear deformation and initial imperfection for direct analysis" , *Engineering Structures*, no. 199, pp.109586, Nov. 2019. https://doi.org/10.1016/j.engstruct.2019.109586

[68] Z.C. Fasoulakis, X.A. Lignos, T.P. Avraam, S.P. Katsatsidis, "Investigation on single-bolted cold-formed steel angles with geometric imperfections under compression" , *Journal of Constructional Steel Research*, no. 162, pp.105733, Nov. 2019. https://doi.org/10.1016/j.jcsr.2019.105733

[69] A. Beyer, N. Boissonnade, A. Khelil, A. Bureau, "Influence of assumed geometric and material imperfections on the numerically determined ultimate resistance of hot-rolled U-shaped steel members" , *Journal of Constructional Steel Research*, no. 147, pp.103–115, Aug. 2018. https://doi.org/10.1016/j.jcsr.2018.03.021

[70] Z. Sadovský, J. Kriváček, V. Ivančo, A. Ďuricová, "Computational modelling of geometric imperfections and buckling strength of cold-formed steel" , *Journal of Constructional Steel Research*, no. 78, pp.1–7, Nov. 2012. https://doi.org/10.1016/j.jcsr.2012.06.005

[71] J.M.F.. Holst, J.M. Rotter, C.R. Calladine, "Imperfections and buckling in cylindrical shells with consistent residual stresses" , *Journal of Constructional Steel Research*, no. 54, pp.265–282, May 2000. https://doi.org/10.1016/S0143-974X(99)00047-4

[72] J. Shen, M.A. Wadee, "Sensitivity to local imperfections in inelastic thin-walled rectangular hollow section struts" , *Structures*, no. 17, pp.43–57, 2019. https://doi.org/10.1016/j.istruc.2018.12.006

[73] F. Walport, L. Gardner, D.A. Nethercot, "Equivalent bow imperfections for use in design by second order inelastic analysis" , *Structures*, no. 26, pp.670–685, Aug. 2020. https://doi.org/10.1016/j.istruc.2020.03.065

[74] J. Sorić, "Imperfection sensitivity of internally-pressurized torispherical shells" , *Thin-Walled Structures*, no. 23, pp.57–66, Jan. 1995. https://doi.org/10.1016/0263-8231(95)00004-W

[75] Z. Lu, H. Obrecht, W. Wunderlich, "Imperfection sensitivity of elastic and elastic-plastic torispherical pressure vessel heads" , *Thin-Walled Structures*, no. 23, pp.21–39, Jan. 1995. https://doi.org/10.1016/0263-8231(95)94359-2

[76] C.K. Mak, K. Der-Wang, "Finite element analysis of buckling and post-buckling behaviors of arches with geometric imperfections" , *Computers and Structures*, no. 3, pp.149–161, Jan. 1973. https://doi.org/10.1016/0045-7949(73)90080-1

[77] Y. Zhou, W. Chang, I. Stanciulescu, "Non-linear stability and remote unconnected equilibria of shallow arches with asymmetric geometric imperfections" , *International Journal of Non-Linear Mechanics*, no. 77, pp.1–11, Dec. 2015. https://doi.org/10.1016/j.ijnonlinmec.2015.06.015

[78] P.C. Vales, M.C. Ribera, M.F. Ballester, F.M. Carvajal, "Compression behaviour of trapezoidal steel sheets with transverse corrugations" , *Steel Construction*, no. 12, pp.215–221, Aug. 2019. https://doi.org/10.1002/stco.201900017

[79] C.A. Dimopoulos, C.J. Gantes, "Nonlinear in-plane behavior of circular steel arches with hollow circular cross-section" , *Journal of Constructional Steel Research*, no. 64, pp.1436–1445, Dec. 2008. https://doi.org/10.1016/j.jcsr.2008.01.005

[80] D. Camotim, C. Basaglia, N. Silvestre, "GBT buckling analysis of thin-walled steel frames: A state-of-the-art report" , *Thin-Walled Structures*, no. 48, pp.726–743, Oct. 2010. https://doi.org/10.1016/j.tws.2009.12.003

[81] N. Silvestre, A.P.C. Duarte, J.P. Martins, L.S. da Silva, "GBT Buckling Analysis of Cylindrical Panels Under

Compression” , *Structures*, no. 17, pp.34–42, Feb. 2019. https://doi.org/10.1016/j.istruc.2018.12.007
[82] A.D. Martins, N. Silvestre, “Modal analysis and imperfection sensitivity of the post-buckling behaviour of cylindrical steel panels under in-plane bending” , *Engineering Structures*, no. 207, pp.110127, Mar. 2020. https://doi.org/10.1016/j.engstruct.2019.110127
[83] V.K. Verma, “Thin-walled curved beams. I: Formulation of Nonlinear Equations” , *Journal of Engineering Mechanics*, no. 122, pp.483–483, May 1996. https://doi.org/10.1061/(ASCE)0733-9399(1996)122:5(483)
[84] Y.J. Kang, C.H. Yoo, “Thin-walled curved beams. II: Analytical solutions for buckling of arches” , *Journal of Engineering Mechanics*, no. 120, pp.2102–2125, Oct. 1994. https://doi.org/10.1061/(ASCE)0733-9399(1994)120:10(2102)
[85] H.R. Meyer-Piening, R. Anderegg, “Buckling and postbuckling investigations of imperfect curved stringer-stiffened composite shells. Part A: Experimental investigation and effective width evaluation” , *Thin-Walled Structures*, no. 23, pp.323–338, Jan. 1995. https://doi.org/10.1016/0263-8231(95)94360-6
[86] M.A. Stiftinger, I.C. Skrna-Jakl, F.G. Rammerstorfer, “Buckling and postbuckling investigations of imperfect curved stringer-stiffened composite shells. Part B: Computational investigations” , *Thin-Walled Structures*, no. 23, pp.339–350, Jan. 1995. https://doi.org/10.1016/0263-8231(95)00021-5
[87] R.S. Srinivasan, L.S. Ramachandra, “Axisymmetric buckling and post-buckling of bimodulus annular plates”, *Engineering Structures*, no. 11, pp.195–198, Jul. 1989. https://doi.org/10.1016/0141-0296(89)90007-2
[88] A.F. Mateus, J.A. Witz, “Parametric study of the post-buckling behaviour of steel plates” , *Engineering Structures*, no. 23, pp.172–185, Feb. 2001. https://doi.org/10.1016/S0141-0296(00)00005-5
[89] L. Gardner, A. Fieber, L. Macorini, “Formulae for Calculating Elastic Local Buckling Stresses of Full Structural Cross-sections” , *Structures*, no. 17, pp.2–20, Feb. 2019. https://doi.org/10.1016/j.istruc.2019.01.012
[90] Y.-L.L. Pi, N.S.S. Trahair, “Non-linear buckling and postbuckling of elastic arches” , *Engineering Structures*, no. 20, pp.571–579, Jul. 1998. https://doi.org/10.1016/S0141-0296(97)00067-9
[91] M.A. Bradford, Y.L. Pi, G. Yang, X.C. Fan, “Effects of approximations on non-linear in-plane elastic buckling and postbuckling analyses of shallow parabolic arches” , *Engineering Structures*, no. 101, pp.58–67, Oct. 2015. https://doi.org/10.1016/j.engstruct.2015.07.008
[92] C.-F. Hu, Y.-M. Huang, “In-plane nonlinear elastic stability of pin-ended parabolic multi-span continuous arches” , *Engineering Structures*, no. 190, pp.435–446, Jul. 2019. https://doi.org/10.1016/j.engstruct.2019.04.013
[93] D. Kim, R.A. Chaudhuri, “Postbuckling behavior of symmetrically laminated thin shallow circular arches” , *Composite Structures*, no. 87, pp.101–108, Jan. 2009. https://doi.org/10.1016/j.compstruct.2008.01.005
[94] E.H. Boutyour, H. Zahrouni, M. Potier-Ferry, M. Boudi, “Asymptotic-numerical method for buckling analysis of shell structures with large rotations” , *Journal of Computational and Applied Mathematics*, no. 168, pp.77–85, Jul. 2004. https://doi.org/10.1016/J.CAM.2003.05.010
[95] A.D. Martins, N. Silvestre, “Modal analysis of the post-buckling behaviour of cylindrical steel panels under compression: Imperfection sensitivity and local2 interaction” , *Thin-Walled Structures*, no. 144, pp.106345, Nov. 2019. https://doi.org/10.1016/j.tws.2019.106345
[96] J. Zhu, M.M. Attard, D.C. Kellermann, “In-plane nonlinear buckling of circular arches including shear deformations” , *Archive of Applied Mechanics*, no. 84, pp.1841–1860, 2014. https://doi.org/10.1007/s00419-014-0890-6
[97] Y.L. Pi, M.A. Bradford, B. Uy, “In-plane stability of arches” , *International Journal of Solids and Structures*, no. 39, pp.105–125, Jan. 2001. https://doi.org/10.1016/S0020-7683(01)00209-8
[98] M.A. Bradford, B. Uy, Y.-L. Pi, “In-Plane Elastic Stability of Arches under a Central Concentrated Load” , *Journal of Engineering Mechanics*, no. 128, pp.710–719, Jul. 2002. https://doi.org/10.1061/(ASCE)0733-9399(2002)128:7(710)
[99] H. Lu, A. Liu, Y.L. Pi, M.A. Bradford, J. Fu, Y. Huang, “Localized loading and nonlinear instability and post-instability of fixed arches” , *Thin-Walled Structures*, no. 131, pp.165–178, Oct. 2018. https://doi.org/10.1016/j.tws.2018.06.019
[100] M. Bateni, M.R.R. Eslami, “Non-linear in-plane stability analysis of FG circular shallow arches under uniform radial pressure” , *Thin-Walled Structures*, no. 94, pp.302–313, Sep. 2015. https://doi.org/10.1016/j.tws.2015.04.019
[101] S. Yan, X. Shen, Z. Jin, “Instability of imperfect non-uniform shallow arch under uniform radial pressure for pinned and fixed boundary conditions” , *Thin-Walled Structures*, no. 132, pp.217–236, Nov. 2018. https://doi.org/10.1016/j.tws.2018.08.018
[102] S. Jin, Z. Li, F. Huang, D. Gan, R. Cheng, G. Deng, “Constrained shell finite element method for elastic buckling analysis of thin-walled members” , *Thin-Walled Structures*, no. 145, pp.106409, Dec. 2019. https://doi.org/10.1016/J.TWS.2019.106409
[103] J.K. Paik, J.K. Seo, “Nonlinear finite element method models for ultimate strength analysis of steel stiffened-plate structures under combined biaxial compression and lateral pressure actions-Part II: Stiffened panels” ,

Thin-Walled Structures, no. 47, pp.998–1007, Aug. 2009. https://doi.org/10.1016/j.tws.2008.08.006
[104] S. Ádány, "Constrained shell Finite Element Method for thin-walled members, Part 1: constraints for a single band of finite elements" , *Thin-Walled Structures*, no. 128, pp.43–55, Jul. 2018. https://doi.org/10.1016/j.tws.2017.01.015
[105] S. Ádány, D. Visy, R. Nagy, "Constrained shell Finite Element Method, Part 2: application to linear buckling analysis of thin-walled members" , *Thin-Walled Structures*, no. 128, pp.56–70, Jul. 2018. https://doi.org/10.1016/j.tws.2017.01.022
[106] S. Ádány, "Modal identification of thin-walled members by using the constrained finite element method" , *Thin-Walled Structures*, no. 140, pp.31–42, Jul. 2019. https://doi.org/10.1016/j.tws.2019.03.029
[107] S. Ádány, "Shell element for constrained finite element analysis of thin-walled structural members" , *Thin-Walled Structures*, no. 105, pp.135–146, Aug. 2016. https://doi.org/10.1016/j.tws.2016.04.012
[108] M. Maali, A.C. Aydın, H. Showkati, M. Sağıroğlu, M. Kılıç, "The effect of longitudinal imperfections on thin-walled conical shells" , *Journal of Building Engineering*, no. 20, pp.424–441, Nov. 2018. https://doi.org/10.1016/j.jobe.2018.08.005
[109] A.T. Sarawit, Y. Kim, M.C.M. Bakker, T. Peköz, The finite element method for thin-walled members-applications, in: Thin-Walled Struct., Elsevier, Feb. 2003: pp. 191–206. https://doi.org/10.1016/S0263-8231(02)00087-3
[110] M.C.M. Bakker, T. Peköz, The finite element method for thin-walled members - Basic principles, in: Thin-Walled Struct., Elsevier, Feb. 2003: pp. 179–189. https://doi.org/10.1016/S0263-8231(02)00086-1
[111] V. Ungureanu, D. Dubina, "Recent research advances on ECBL approach. Part I: Plastic-elastic interactive buckling of cold-formed steel sections" , *Thin-Walled Structures*, no. 42, pp.177–194, Feb. 2004. https://doi.org/10.1016/S0263-8231(03)00056-9
[112] M. Kotełko, "Load-capacity estimation and collapse analysis of thin-walled beams and columns - Recent advances" , *Thin-Walled Structures*, no. 42, pp.153–175, Feb. 2004. https://doi.org/10.1016/S0263-8231(03)00055-7
[113] A. Teter, Z. Kolakowski, "Interactive buckling and load carrying capacity of thin-walled beam-columns with intermediate stiffeners" , *Thin-Walled Structures*, no. 42, pp.211–254, Feb. 2004. https://doi.org/10.1016/S0263-8231(03)00058-2
[114] P. Casariego, M. Casafont, M. Ferrer, F. Marimon, "Analytical study of flat and curved trapezoidal cold formed steel sheets by means of the yield line theory. Part 2: Curved sheets with transverse corrugations" , *Thin-Walled Structures*, no. 141, pp.693–712, Aug. 2019. https://doi.org/10.1016/j.tws.2018.12.018
[115] I.D. Thanasoulas, C.E. Douthe, C.J. Gantes, X.A. Lignos, "Influence of roller-bending on RHS steel arches: Experimental and numerical investigation" , *Thin-Walled Structures*, no. 131, pp.668–680, Oct. 2018. https://doi.org/10.1016/j.tws.2018.07.027
[116] W.M. Quach, J.G. Teng, K.F. Chung, "Finite element predictions of residual stresses in press-braked thin-walled steel sections" , *Engineering Structures*, no. 28, pp.1609–1619, Sep. 2006. https://doi.org/10.1016/j.engstruct.2006.02.013
[117] C.D. Moen, T. Igusa, B.W.W. Schafer, "Prediction of residual stresses and strains in cold-formed steel members" , *Thin-Walled Structures*, no. 46, pp.1274–1289, Nov. 2008. https://doi.org/10.1016/j.tws.2008.02.002
[118] W.M. Quach, J.G. Teng, K.F. Chung, "Residual stresses in steel sheets due to coiling and uncoiling: A closed-form analytical solution" , *Engineering Structures*, no. 26, pp.1249–1259, Jul. 2004. https://doi.org/10.1016/j.engstruct.2004.04.005
[119] S.H. Li, G. Zeng, Y.F. Ma, Y.J. Guo, X.M. Lai, "Residual stresses in roll-formed square hollow sections" , *Thin-Walled Structures*, no. 47, pp.505–513, May 2009. https://doi.org/10.1016/j.tws.2008.10.015
[120] Q. Han, Z. Han, Y. Lu, "Experimental and numerical investigations on residual stresses in hot-bent circular steel tube" , *Journal of Constructional Steel Research*, no. 161, pp.31–46, Oct. 2019. https://doi.org/10.1016/j.jcsr.2019.06.008
[121] D. Kollár, B. Kövesdi, "Welding simulation of corrugated web girders - Part 2: Effect of manufacturing on shear buckling resistance" , *Thin-Walled Structures*, no. 141, pp.477–488, Aug. 2019. https://doi.org/10.1016/j.tws.2019.04.035
[122] D. Kollár, B. Kövesdi, "Welding simulation of corrugated web girders - Part 1: Effect of manufacturing on residual stresses and imperfections" , *Thin-Walled Structures*, pp.106107, May 2019. https://doi.org/10.1016/j.tws.2019.04.006
[123] H. Amouzegar, B.W. Schafer, M. Tootkaboni, "An incremental numerical method for calculation of residual stresses and strains in cold-formed steel members" , *Thin-Walled Structures*, no. 106, pp.61–74, Sep. 2016. https://doi.org/10.1016/j.tws.2016.03.019
[124] Y. Yao, W.M. Quach, B. Young, "Finite element-based method for residual stresses and plastic strains in cold-formed steel hollow sections" , *Engineering Structures*, no. 188, pp.24–42, Jun. 2019.

https://doi.org/10.1016/j.engstruct.2019.03.010
[125] W. Liu, K.J.R. Rasmussen, H. Zhang, "Modelling and probabilistic study of the residual stress of cold-formed hollow steel sections" , *Engineering Structures*, no. 150, pp.986–995, Nov. 2017. https://doi.org/10.1016/j.engstruct.2017.08.004
[126] M.M. Pastor, J. Bonada, F. Roure, M. Casafont, "Residual stresses and initial imperfections in non-linear analysis" , *Engineering Structures*, no. 46, pp.493–507, Jan. 2013. https://doi.org/10.1016/j.engstruct.2012.08.013
[127] A. Mutafi, N. Yidris, J. Loughlan, R. Zahari, M.R. Ishak, "Investigation into the distribution of residual stresses in pressed-braked thin-walled steel lipped channel sections using the 3D-FEM technique" , *Thin-Walled Structures*, no. 135, pp.437–445, Feb. 2019. https://doi.org/10.1016/j.tws.2018.11.003
[128] I.C. Noyan, J.B. Cohen, Residual Stress. Measurement by Diffraction and Interpretation, Springer-Verlag, New York, 2013
[129] M. Howes, T. Inoue, M. Park, Handbook of Residual Stress and Deformation of Steel, ASM International, 2002.

Doświadczalne i obliczeniowe podejście do oceny struktur łukowych z blach podwójnie giętych. Przegląd najnowszych osiągnięć

Słowa kluczowe: K-span, strukury łukowe, blachy stalowe podwojnie gięte, imperfekcje, Cyfrowa Koleracja Obrazu, Metoda Elementów Skończonych

Streszczenie:

Podwójnie gięte, samonośne struktury łukowe systemu K-span, stosowane są obecnie na runku światowym do wykonywania zadaszeń obiektów budowlanych jako alternatywna technologia w odniesieniu do tradycyjnych rozwiązań. System konstrukcyjny K-span zyskał popularność głównie z powodu prostej i taniej metody wytwarzania oraz szybkiego montażu. Obecnie powstają nowe odmiany tego sytemu, jednak nadal brak jest odpowiedniego sposobu projektowania. Trudności w projektowaniu są jedną z przyczyn awarii a nawet katastrof tego typu struktur. W latach osiemdziesiątych ubiegłego stulecia powstały pierwsze opracowania studialne dotyczące analiz badawczych i obliczeniowych zadaszeń łukowych z blach podwójnie giętych. Stanowiły one podstawy rozwoju dzisiejszej technologii systemu K-span, jednak straciły walory praktyczne z uwagi na zmieniające się uwarunkowania techniczne. Artykuł stanowi przegląd rozwoju technik badawczych i obliczeniowych dotyczących struktur łukowych z blach podwójnie giętych. W artykule przedstawiono wybrane prace naukowe, które były podstawą rozwoju technik badawczych i metod obliczeniowych a także ich współczesną kontynuację.

Pomimo bogatej historii rozwoju technologii wytwarzania i stosowania struktur łukowych z podwójnie giętych blach stalowych, projektowanie tego typu konstrukcji nadal może być problematyczne. Konsekwencje takiego stanu wiedzy mogą być dotkliwe z uwagi na możliwość występowania awarii a nawet katastrof. W związku z tym, prace naukowe dotyczące tych zagadnień powinny być nadal kontynuowane tym bardziej, że w chwili obecnej nie ma norm projektowych przystosowanych do projektowania struktur łukowych z blach podwójnie giętych.

Zdaniem autorów publikacji, dalszy rozwój prac analitycznych będzie skupiał się głównie w obszarze doskonalenia metod obliczeń zwłaszcza w zakresie interakcji niestateczności globalnej i lokalnej oraz w kierunku zagadnień związanych z wpływem naprężeń resztkowych na właściwości stali przy głębokim tłoczeniu profilu. Przypuszczalnie analizy te będą realizowane z wykorzystaniem numerycznych metod obliczeń metodą elementów skończonych, bądź też metod hybrydowych eksperymentalno-numerycznych. W chwili obecnej ważną rolę w rozwoju prac eksperymentalnych stanowią nowe techniki pomiarowe a w szczególności metoda wizyjna tj.: Cyfrowa Korelacja Obrazu, która stosowana jest do pomiaru przemieszczeń i odkształceń dużych struktur. Metoda ta daje nieporównywalnie większe możliwości

pomiarowe w porównaniu do metod tradycyjnych, co bezpośrednio przekłada się na dokładność i jakość uzyskanych wyników badań.

Przegląd rozwiązań i analiz naukowych, przedstawiony w tym artykule jest podsumowaniem dotychczasowej wiedzy autorów w tym zakresie. Artykuł jest również prognozą przyszłych kierunków rozwoju badań i analiz struktur łukowych z blach podwójnie giętych.

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