A R C H I T E C T U R E C I V I L E N G I N E E R I N G E N V I R O N M E N T
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NUMERICAL MODELS OF ABM K-SPAN STEEL ARCH PANELS

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Abstract
This paper describes briefly the ABM (Automatic Building Machine) technology which can be used as a solution for buildings and roofing structures. It is a factory on wheels that makes cold-formed arch steel buildings in a very short time period as self-supporting panels. This technology was commonly used by US army to built temporary buildings and nowadays those structures become popular solution in civilian life. There are two main problems connected with this technology. First one, is lack of proper theoretical model of the structure and second one, that all calculations are made according to American design codes which are not always compatible with European standards. In order to bend ABM panel as an arch, its surfaces become folded. This leads to the cross-section losses in axial and bending stiffness but also gives some positive aspects. The walls of the cross-sections are less vulnerable to local buckling. In this paper the following is investigated: linear and nonlinear analyses of axial, bending and torsional stiffness. Analysis of panel's plastic behavior and buckling analysis are also briefly described. These numerical analyses are made due to better understanding of folding influence on ABM panel. Having this knowledge will give us an idea about spans of the arches made in this technology.

Streszczenie
Artykuł ten zwięźle przedstawia technologię ABM wykorzystywaną do budowy hal oraz przykryć dachowych. System ten składa się z mobilnej maszyny, która produkuje zimno gięte, stalowe, samonośne, łukowe panele, które to po złączeniu tworzą gotową konstrukcję. System ten był często wykorzystywany w amerykańskiej armii dla wznoszenia tymczasowych budynków. W dzisiejszych czasach, system ten jest coraz bardziej popularny w budownictwie lądowym. Z technologia tą związane są dwa podstawowe problemy. Pierwszy, to brak modelu teoretycznego opisującego zachowanie elementu ABM. Drugi, to brak algorytmu obliczeniowego według norm europejskich. Większość dotychczas wykonanych obliczeń przeprowadzono zgonie z wytycznymi amerykańskimi, które nie zawsze są kompatybilne z normami obowiązującymi w Europie. Podczas formowania elementu ABM w łuk, powstają na jego powierzchni poprzeczne fałdowania. Fałdowanie te prowadzą do strat w podłużnej i giętej sztywności, ale mogą mieć pozytywny wpływ na stateczność lokalną profilu. W artykule przedstawiono wyniki z analizy liniowej i nieliniowej dla sztywności podłużnej, giętej i skrętnej. Przedstawiono również, analizę w zakresie plastycznych odkształceń oraz analizę wyboczenia profilu ABM. Rozważania te mają pomóc zrozumieć wpływ poprzecznego fałdowania elementu na jego sztywność oraz określić w przyszłości maksymalną rozpiętość stalowych hal łukowych budowanych w opisywanym systemie.

Keywords: **ABM; K-span; MIC 120; Cold-formed; Steel; Arch; Folding; Geometry; Model.**

1. INTRODUCTION

Due to today's difficult economy, cheap and short time consuming solutions for buildings industry are very desirable. One of the solutions which fulfills above requirements is the ABM (Automatic Building Machine) technology. It is a mobile factory used to fabricate and construct K-span arch steel buildings based on self-supporting panels made of MIC 120 and MIC 240 profiles. This technology comes from the USA and belongs to M.I.C. Industries Inc. [7]. In Poland there are two companies specializing in this building system. First one, Konsorcjum Hale Stalowe [5] uses MIC 120 profiles (Fig. 1a). Second one, Węglopol Sp z o.o.[11] uses MIC 240 profiles (Fig. 1b). In this paper only MIC 120 profiles are considered.

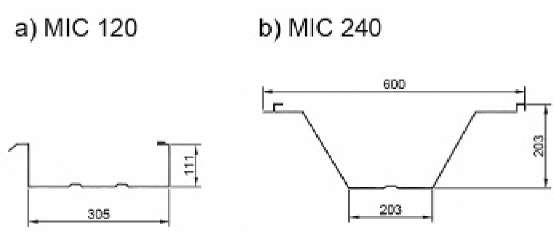

Figure 1.
MIC 120 and MIC 240 cross-sections [2]

The ABM is transported via truck to the construction site. Firstly, the panels are formed and cut to achieve needed span. Secondly, those panels are curved to form the arches. Each of curved panels are assembled together to form the structure. The maximum spans which can be achieved for these structures in Poland are not known yet due to a few important problems described below.

According to authors' knowledge, all calculations are made according to American design codes. This gives a series limitation of use of this system in Europe due to different loads consideration. Also, there is no proper theoretical panel model and surfaces folding created during panels bent into arch is not well understood. European standards [4] recommend to treat ABM panel's cross-section as class 4. So it means that folded surfaces are not taken into calculation process. It is not totally correct especially that folding gives some resistance to local buckling. This paper will try to give a starting point for better understanding of folding influence on ABM MIC 120 panels. According to authors, this problem in not well recognized and there are no publications about this topic. The overall introduction to ABM technology and their problems are well described by Walentyński [10] and Cybulski [3]. There is also one publication by Kowal [6], where author tries to do calculations of bearing capacity of MIC 210 profile based on Eurocodes and German Standards.

2. CONSTRUCTION PROCESS IN ABM TECHNOLOGY

The ABM technology consists of a movable, steel building manufacturing plant, known as the MIC 120 System. This machine is placed on a trailer, forming factory on wheels which can be easily transported to any construction sites (see Figure 2). Once, the machine is delivered to site, the construction process can be started by a small group of trained crew.

Figure 2.
ABM MIC 120 machine [2]

Firstly, coils of steel are formed to the straight panels with cross-section presented in Figure 1. This panel is cut to achieve needed span of the future arch building. Secondly, these panels are bent to form the arch and their cross-section changes to the one presented in Figure 10. The sketch of this process is shown in Figure 3.

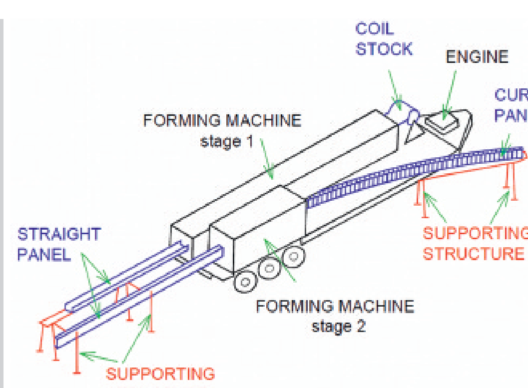

Figure 3.
Panels manufacturing process [9]

Figure 4.
Panels assembly

Figure 5.
Panels assembly

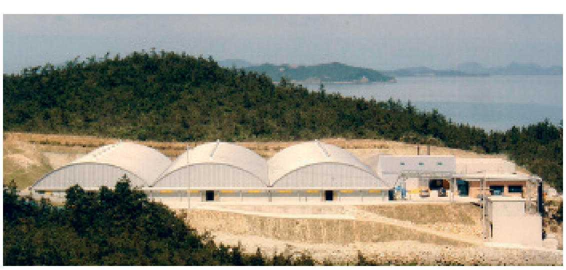

Figure 6.
Ready structure in South Korea

Few single panels are tight together by the seam machine to form groups of panels which are fixed to lifting sling and transported to the execution place by a crane (see Figures 4 and 5).

After that these panels groups are machine seamed together, they form an economical and waterproof steel structure. Ready K-Span, arch steel building made in this technology is presented in Figure 6.

3. INTRODUCTION TO STIFFNESS INVESTIGATION

3.1. Model description

Two general types of shell models made in Abaqus [1] are considered for numerical analyses. First one, with folded surfaces, simulates real geometry of the MIC 120 profile (Figure 7).

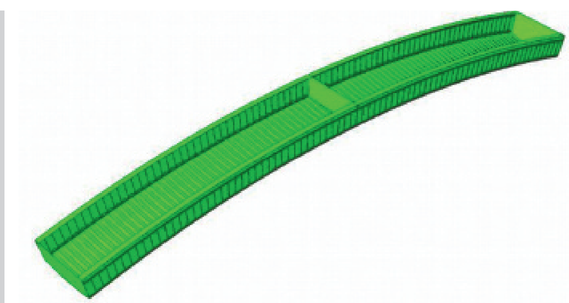

Figure 7.
MIC 120 model

Second one, with smooth surfaces, is used for comparison with the first one and for better understanding of folding influence on the ABM panels (Figure 8).

Both models were built as arch shell models with 2.73 m long span and with rise of arch equal to 0.19 m. Samples are cut from the circle of radius 5 m. The dimensions are chosen due to future laboratory tests. The static schemes are considered as pin and simply supported arches with the boundary conditions as follows:

1. Supports on each ends have disabled movements in X,Y and Z directions and rotations about X and Z axes. This model is used to simulate the work of a

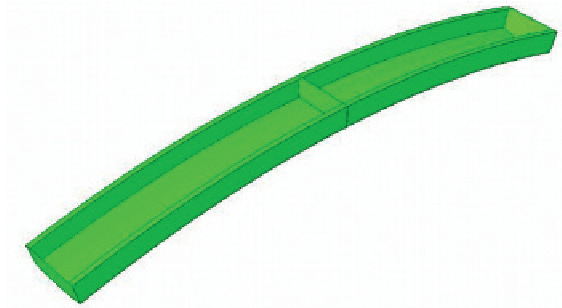

Figure 8.
Panel with smooth surfaces

single panel and will be called FP1 for folded panel and SP1 for smooth panel (Figure 9a).

2. Support on one end has the same properties as above. Support on the other end has enabled movement in X direction. This model is used to simulate the work of a single panel and will be called FP2 for folded panel and SP2 for smooth panel (Figure 9b).

The profile cross-section with area of 600 mm^2 and used coordinate system are presented in Figure 10. This cross-section represents panel without folding and has some geometrical simplifications due to modeling reasons.

Two analyses for each model were provided: linear and nonlinear (large displacement method) with material modeled as isotropic, elastic (Young modulus E=210 GPa, Poisson ratio ν=0.3). The analysis of material plastic behavior is only made for FP1 model. Loading conditions will be described afterwards. Three plates (on each end and in the middle) are used for applying loads and support. These plates are modeled as "rigid bodies".

3.2. Analysis of the ABM panel with folded surfaces in elastic state

Firstly FP1 numerical model was loaded in mid span by the concentrated load equal to F_1=8.5 kN. Values of displacements are read from node 1 (upper corner), node 2 (lower corner) and node 3 (in the middle of lower flange). Nodes positions are showed in Figure 10. These nodes are placed 0.6 m away from the mid span. Deformed shape of this panel is shown in Figure 11.

For FP2 model the concentrated load F_2=3 kN was chosen and deformed shape of this model is displayed in Figure 12. The displacements are read from node 4 (movable end).

The analyses results are presented in Tables 1 and 2.

From the tables above it is observed that nonlinear analysis does not influence much vertical displacements Uz (difference by about 6%). When it comes to horizontal displacements Uy measured on the free corner (node 1), the difference between linear and nonlinear analyses is equal to 22%. For the bottom corner (node 2) this difference becomes even larger.

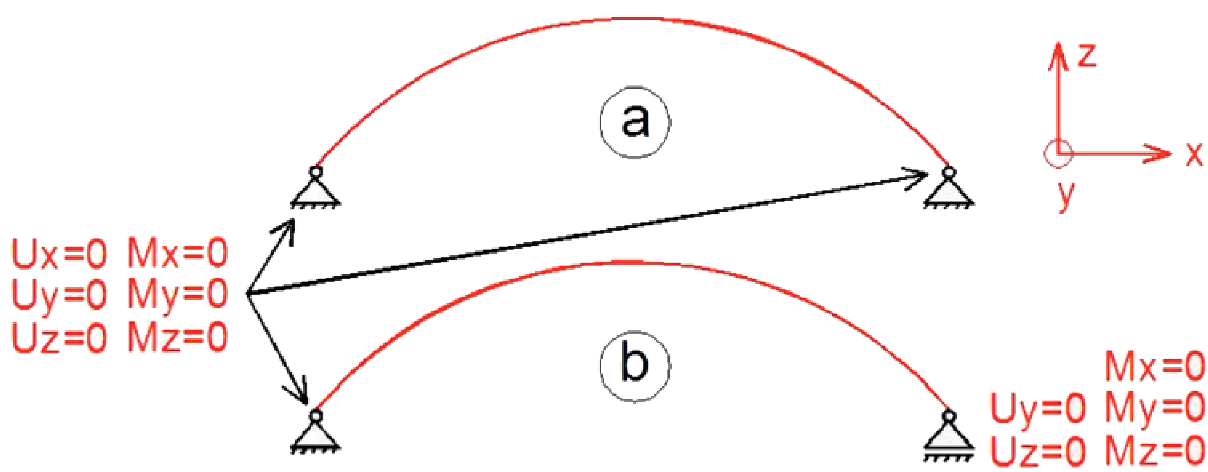

Figure 9.
Statics schemes used in simulations

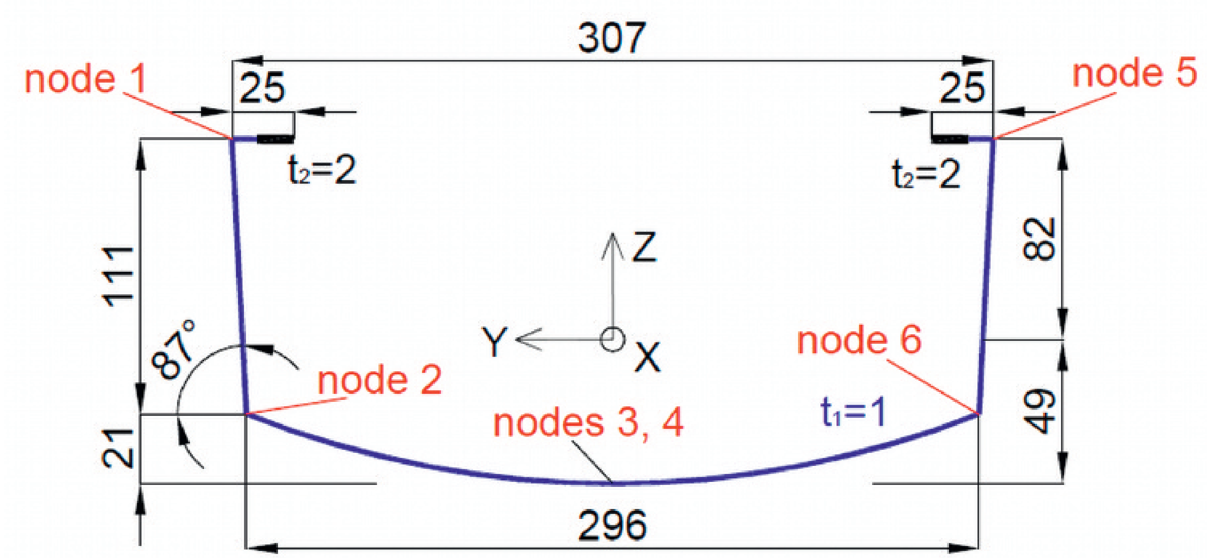

Figure 10.
The profile cross-section

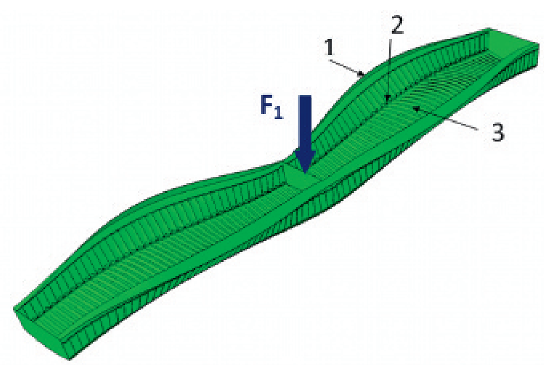

Figure 11.
Deformed shape of FP1 model

Table 1.
Displacement values of FP1 model

	Linear analysis		Nonlinear analysis	
Node's no.	Uy [mm]	Uz [mm]	Uy [mm]	Uz [mm]
1	2.08	-2.68	2.67	-2.84
2	0.10	-2.65	0.13	-2.75
3	0	-2.19	0	-2.14

Table 2.
Displacement values of FP2 model

	Linear	Nonlinear
Node's no.	Ux [mm]	Ux [mm]
4	-5.21	-5.00

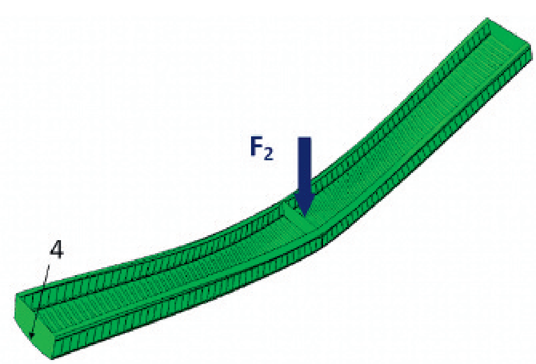

Figure 12.
Deformed shape of FP2 model

It seems that for FP1 model nonlinear analysis can play important role due to results differences. Now, looking at these results by means of values magnitude, it can be stated that these differences achieved from both analyses are meaningless.

The same observations are made for longitudinal displacements Ux using FP2 model. 4% difference was achieved from both analyses but looking at it from the point of values magnitude, this difference can be also neglected.

Secondly, FP1 model was loaded in mid span by a pair of concentrated loads equal to F=3 kN each. This analysis was done for torsion investigation (Figure 13).

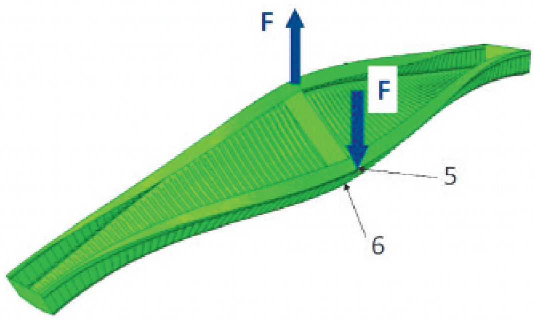

Figure 13.
Torsional analysis of FP1 model

The displacements values of this analysis are read from node 5 (upper corner) and node 6 (lower corner) which are placed in arch's mid span and are presented in Table 3.

Table 3.
Displacements from torsional analysis of FP1 model

	Linear analysis		Nonlinear analysis	
Node's no.	Uy [mm]	Uz [mm]	Uy [mm]	Uz [mm]
5	-5.90	-3.62	-5.86	-3.77
6	-3.30	-3.49	-3.26	-3.60

Also, in this case the nonlinear analysis seems to be unnecessary.

Thirdly, linear buckling analysis was done for FP1 model with loading pattern described in Figure 11. Only two buckling modes are presented in this paper: first and third one (Figures 14 and 15). Third buckling mode will never appear and is only shown for results comparison.

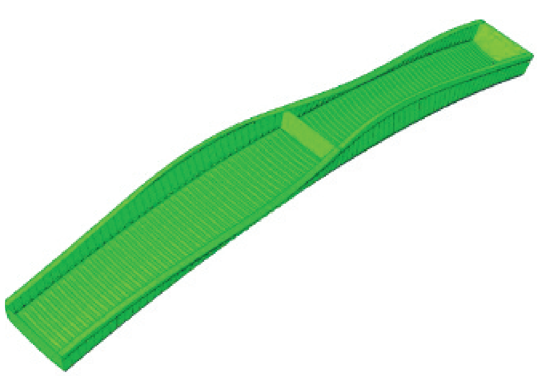

Figure 14.
First, global (distortional) buckling mode

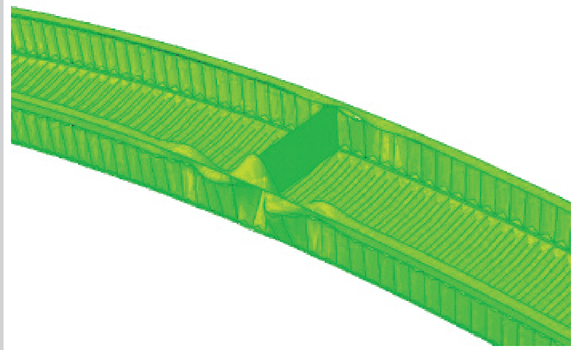

Figure 15.
Third, local buckling mode

The values of achieved critical loads are presented in Table 4.

Table 4.
FP1 buckling analysis

	Eigen value	Critical load [kN]
Global behavior	1.92	16.3
Local behavior	2.77	23.5

From above buckling analysis, it is observed that for the ABM panel with folded surfaces, global (distortional) buckling mode occurs before the local one.

3.3. Analysis of the ABM panel with folded surfaces in plastic state

FP1 model was loaded in mid span by a concentrated load equal to F=20 kN (loading pattern is shown in Figure 11). Knowledge about true stresses and strains are needed in order to run analysis of plastic behavior of steel in Abaqus.

From EC [4] nominal values of basic yield strength f_y and ultimate tensile strength f_u of steel are available. Values of nominal strains can be found on the "Rolls-Rolls" company website [8]. These values are also called engineering stresses and strains and they do not take into account materials deformations. Based on Abaqus tutorial, conversion of nominal stress/strain values to the true ones is presented by using following equations:

– for nominal strain:

$$\varepsilon_{nom} = \frac{\sigma_{nom}}{E}, \tag{1}$$

– for true strain:

$$\varepsilon = \ln(1 + \varepsilon_{nom}), \tag{2}$$

– for true stress:

$$\sigma = \sigma_{nom}(1 + \varepsilon_{nom}), \quad (3)$$

– for plastic strain:

$$\varepsilon^{pl} = \varepsilon - \frac{\sigma}{E}. \quad (4)$$

Equations 1-4 are achieved from empirical investigations.

Assuming f_y=320 MPa, E=210 GPa, f_u=400 MPa with ε_{nom}=0.22 and above equation, values of true stresses and strains are presented in Table 5.

Table 5.
Stress/strain conversion

Nominal stress σ_{nom} [MPa]	Nominal strain ε_{nom}	True stress σ [MPa]	True strain ε	Plastic strain ε^{pl}
320	0.00152	320.5	0.00152	0
400	0.22	488	0.1989	0.197

Using data presented in Table 5 for panel's steel, the analysis was submitted and deformed shape of ABM MIC 120 profile is presented in Figure 16. It is the classical metal plasticity model.

From Figure 16 it is observed that highest values of normal stresses are achieved in folding area and are bigger than value of steel yield strength. Stresses in smooth area are in the elastic range. From this short analysis, it can be stated that together with folding size growth, the bending moments influence on normal stresses increase (comparing with normal forces). This is a reason for higher values of normal stresses in folding area. Figure 17 presents dependence between stresses and strains for one node in horizontal folded area. This relation is not linear.

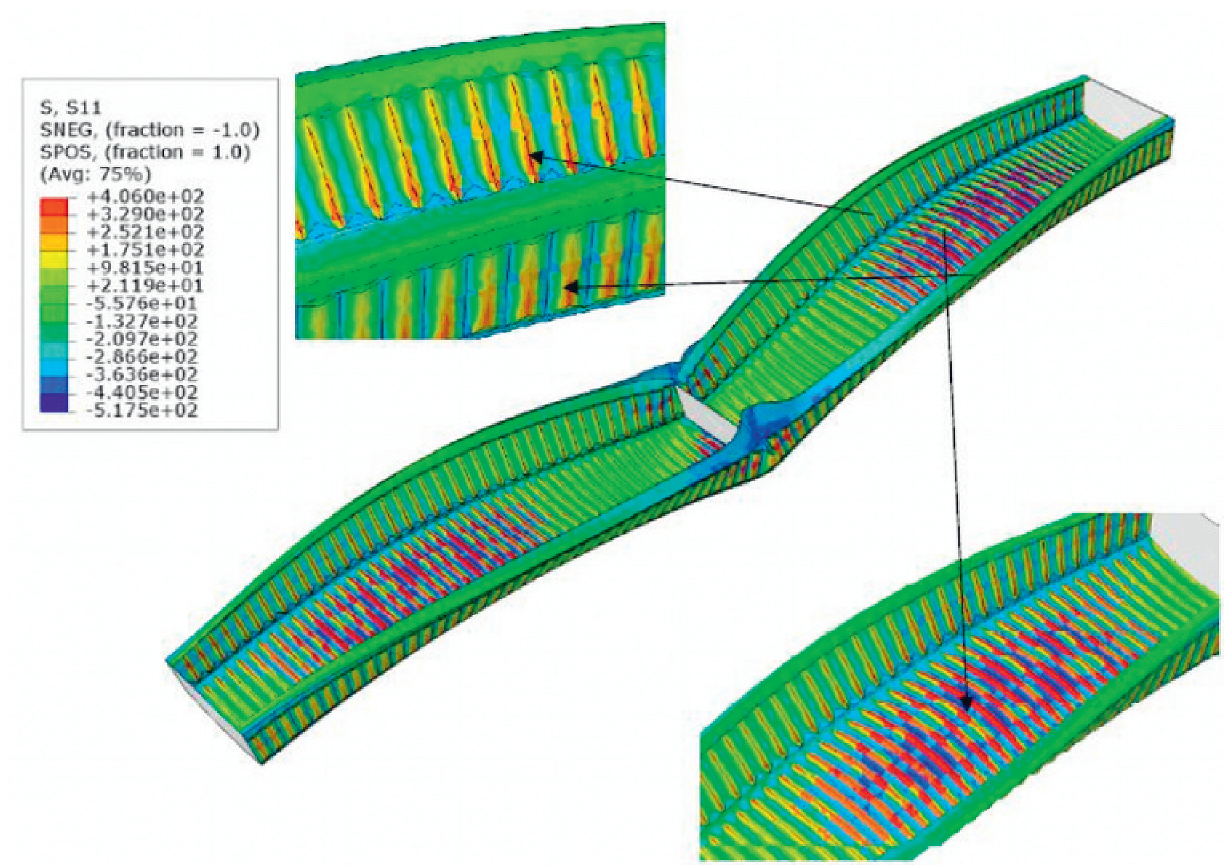

Figure 16.
Plastic behavior of FP1 model

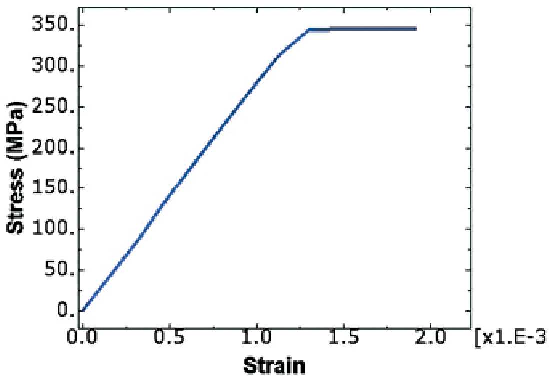

Figure 17.
Stress vs strain

3.4. Analysis of the panel with the smooth surfaces

This kind of panel does not really exist and it was only modeled for comparison purposes. The same analyses were performed as for the ABM panel with folded surfaces. Firstly, SP1 and SP2 were loaded by concentrated loads F_1=8.5 kN and F_2=3 kN respectively. The results are presented in Tables 6 and 7.

Table 6.
Displacement values of SP1 model

	Linear analysis		Nonlinear analysis	
Node's no.	Uy [mm]	Uz [mm]	Uy [mm]	Uz [mm]
1	1.58	-1.57	1.84	-1.64
2	0.19	-1.52	0.20	-1.57
3	0	-0.57	0	-0.52

Table 7.
Displacement values of SP2 model

	Linear	Nonlinear
Node's no.	Ux [mm]	Ux [mm]
4	-2.78	-2.53

Based on displacements values from above tables, it can be stated that there are no significant differences between linear and nonlinear analyses.

Now, displacements results from torsional analysis of SP1 model are shown in Table 8.

Table 8.
Displacement from torsional analysis of SP1 model

	Linear analysis		Nonlinear analysis	
Node's no.	Uy [mm]	Uz [mm]	Uy [mm]	Uz [mm]
5	-5.90	-2.06	-2.96	-2.11
6	-1.50	-1.99	-1.48	-2.02

From above table, it is observed that nonlinear analysis does not affect displacements values.

The linear buckling analysis was performed for SP1 model and eigenvalue and critical load achieved from first buckling mode are displayed below.

Table 9.
SP1 buckling analysis

	Eigen value	Critical load [kN]
Local behavior	1.07	9.06

First mode of buckling analysis have local character and its deformed shape is shown in Figure 18.

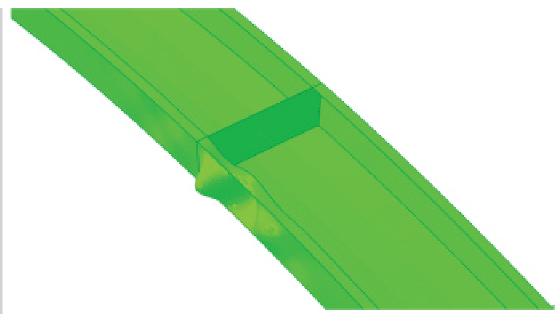

Figure 18.
Local buckling mode of SP1

3.5. Results comparison

This section provides results comparison between linear and nonlinear analyses and the model with and without folded surfaces.

It seems that at this stage of research the nonlinear analysis (geometric nonlinearities) does not influence much achieved results. It is also observed that nonlinear analysis affects more the model with folded surfaces. The differences between both analyses can be neglected due to size of values magnitude.

Under the concentrated load, model with folded surfaces has bigger values of longitudinal and vertical displacements than the model with smooth surfaces (see Tables 1, 2, 6, 7). Taking into consideration results achieved for node 2 of FP1 and SP1 models, it seems that folded panel is more resistant to horizontal displacements (see Tables 1 and 6). This is caused by lower flange folding where node 3 has larger vertical displacements than smooth panel and because of it there is smaller horizontal expansion of cross-section's lower corners.

Taking into account displacements from Tables 3 and 8, the cross-section rotation angles were achieved. For the ABM panel with folded surfaces this rotation angle is equal to 13° and for the smooth panel this value becomes smaller and is equal 8°.

From buckling analyses, it is observed that model with folded surfaces is more resistant to local buckling. First mode of this model was related to global buckling when for model with smooth surfaces, first mode was related to plate local buckling. For the folded panel, local buckling of vertical walls was observed for the third mode and critical force which starts this plate local buckling is around 2.6 times bigger than the critical force achieved for the smooth panel.

4. CONCLUSIONS AND FUTURE WORK

This paper described briefly the ABM technology with panels behavior (with and without folding) under certain load conditions. Linear and nonlinear analyses were performed in Abaqus-Finite Element Method commercial software. The nonlinear analysis was done to check geometric nonlinearities based on large displacement method. So far it was observed that nonlinear analysis can be neglected due to displacements values magnitude and it can be stated that these differences achieved from both analyses are meaningless.

Comparing results from analyses of folded and smooth panels, the following was observed:

- due to surfaces folding, panel's axial, bending and torsional stiffnesses decrease,
- due to surfaces folding, panel is less vulnerable to local buckling and before the buckling occurs, the panels characteristic yield strength (f_y) will be exceeded.

Short analysis of panel's steel plastic behavior was also carried out. It was observed that highest values of normal stresses were achieved in panel's folding area and are bigger than value of steel yield strength.

Information presented in this work, gives a starting point to understanding the ABM panels behavior which should conclude, after more advanced research, in presentation of ABM equivalent panel for engineering purposes (smooth panel with properties of folded one).

Also, laboratory tests are necessary to check achieved results and if needed, to calibrate the numerical model.

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