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Flat pneumatic elements and their potential use in the construction of dwelling facilities within emergency housing systems

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Abstract: As part of this study, experimental and theoretical investigations into the strength and stiffness of flat pneumatic elements to be used in lightweight dwelling structures, enabling the quick assembly of the latter, were undertaken.

On the basis of the experimentally and theoretically determined parameters of the elements it will be possible to design configurations of spatial pneumatic structures.

In particular, the following were devised and carried out:

- a theoretical assessment of the load capacity and stiffness of selected pneumatic elements depending on their dimensions, internal pressure and fixing and support conditions,
- an experimental verification of the obtained results.

This study has an exploratory character and constitutes the basis for the design and implementation of original technical, constructional and architectural solutions relating to the application of spatial pneumatic structures in the emergency system.

It should be mentioned that in the known literature on the subject there is no theoretical basis for designing structures whose principal member is a flat pneumatic element.

In the construction industry such structures have not been used so far. An exemplary solution of the spatial dwelling structure has been patented under the name *Obiekt mieszkalny* (*Dwelling facility*), (patent no. 131 528, of 18.04.1988).

The work is innovative. Apart from the military applications in the USA, mentioned by the author, studies on the subject are unknown. All the more so, it seems that the research is worth continuing as pneumatic components can have many civilian and military applications. Their use in the construction industry would prevent the housing problem in the case of natural disasters or in other more dramatic events.

Keywords: pneumatic structures, spatial pneumatic structure, dwelling facilities

Subject and aim of the study

As part of this study, experimental and theoretical investigations into the strength and stiffness of flat pneumatic elements to be used in lightweight dwelling structures, enabling the quick assembly of the latter, were undertaken. A calculation method and experimental tests for assessing the load-carrying capacity and strength of such elements as the structural components of pneumatic structures need to be developed. The experimentally and theoretically determined parameters of the elements will form the basis for designing configurations of spatial pneumatic structures. The following were devised and carried out:

- a theoretical assessment of the load capacity and stiffness of selected pneumatic elements depending on their dimensions, internal pressure and fixing and support conditions;
- an experimental verification of the obtained results.

In the next stage of this project a prototype or model of the spatial pneumatic structure as a dwelling module is to be made, but first such a system needs to be designed, which comprises:

- formulating a theoretical basis for structural pneumatic components for spatial dwelling modules;
- drawing up technical and technological specifications for manufacturing structural pneumatic components;
- specifying ways of fixing, joining and supporting such components to create spatial dwelling modules out of them;
- specifying conditions and methods for designing function, form and technical solutions within the Emergency Housing Construction System (EHCS); an example of such a solution has been patented under the name *Obiekt mieszkalny (Dwelling facility)* at the Patent Office of the Republic of Poland [3].

This study has an exploratory character and constitutes the basis for the design and implementation of original technical, constructional and architectural solutions relating to the application of spatial pneumatic structures in the Emergency Housing Construction System (EHCS) which is the ultimate objective.

The are several reasons, mainly functional, for undertaking this project since among the existing construction systems there is no system which would make it possible to create such maximally high-standard dwelling conditions in a maximally short time as the planned EHCS based on flat pneumatic elements (pneumatic plates) is capable of creating.

The system was called EHCS with regard to the conditions in which it is to be used. It is intended for erecting dwelling facilities in areas lacking technical infrastructure, for workers carrying out temporary construction/geological work and for explorers in the natural environment. It can be used in the construction of seasonal tourist and sports facilities and also in areas ravaged by war or natural disasters.

EHCS will be based on the pneumatic plate – a basic structural component used to create dwelling modules in any spatial form.

Owing to the light weight of EHCS and to the fact that it can be transported using various means of transport (land, water and air transport), it will be possible to immediately fill in any missing parts in the housing structure in any terrain and subsurface conditions. Prefabricated EHCS dwelling elements will be stored in and transported directly from fabrication plants or regional, national or international banks of EHCS dwellings.

The wall and floor components of the dwelling modules are plates made of a flexible material, stiffened with compressed air from the inside. The plates are joined together by means of flexible connectors, to form multispace dwelling modules having cuboid shapes or other functionally or structurally justified shapes.

The sizes of dwellings in EHCS vary, being a multiplication of the adopted modular system. Each of the dwellings is equipped with utility connections. The wall and floor plates are made of flexible shells characterized by proper elasticity, joined together by a system of tendons and a layer of a porous material constituting a compressed gas holder.

The advantages of this type of construction are:

- high structural and functional flexibility, whereby dwellings can be adjusted to the needs of the family and a particular group of occupants;
- quick assembly and disassembly in any terrain;
- light weight – the weight of the structure per $1m^2$ of dwelling space is 20–40 times lighter than that of a conventionally built building;
- owing to the small dimensions of the uninflated dwelling modules (stored and transported in the form of packets) and their light weight, many means of transport, including air transport in hardly accessible areas, can be used;
- immediate usability thanks to the system of pneumatic furniture, plastic film or organic glass in window openings and the fact that each dwelling is equipped with a kitchen block and a bathroom block, forming a functional and structural whole with the dwelling;
- the maximum adherence to the principle of the inviolability of the natural terrain and environment owing to the temporary character of the development and its peculiar features, such as: no earthworks, and minimum engineering and site enabling works.

In order to implement the EHCS concept the stability and structural properties of the pneumatic plate (walls and floors) and linear elements (columns and beams) need to be theoretically determined and the obtained theoretical relationships must be experimentally verified.

Moreover, possible ways of joining the components as well as the tightness and thermal insulating power of the latter must be determined.

The theoretically and experimentally determined pneumatic element sizes and parameters will provide the basis for designing pneumatic elements and spatial pneumatic structures.

It should be mentioned that in the known literature on the subject there is no theoretical basis for designing structures whose principal component is a flat pneumatic element.

However, it is known that pneumatic plates have been used in the US military aviation industry to build a manned plane whose all structural components (airfoils, stabilizers, the fuselage) are made of flat inflatable elements (pneumatic plates).

In the construction industry such structures have not been used so far (of course, except for linear, nonflat elements, such as arches, ribs, etc.).

The test results presented further in this paper show that the tested element (the plate) resists considerable buckling forces[1], which augurs well for its use for the structural components of EHCS.

Bending test results indicate that within the range of the internal pressures used in the experiment the plate has a very low bending stiffness. This means that in order to increase the plate's bending stiffness one must increase the internal pressure or the cross section.

It follows from the above findings that the flat pneumatic structural components can be used for the load-bearing walls and floors of EHCS dwelling modules, provided that the internal pressures and cross sections of the components are properly matched.

Pneumatic structural components

Theoretical basis for calculating compressive, bending and buckling stiffness of pneumatic structural components

A pneumatic element, in the form of a plate, subjected to internal pressure is considered. The shape and dimensions of the element are shown in figure 1. The element is made of rubberized fabric. Owing to the presence of the fabric in the element's shell the latter has anisotropic properties. The anisotropy comes down to orthotropy whose principal directions coincide with the orientation of the fibres. The directions of the anisotropy are shown in fig. 1.

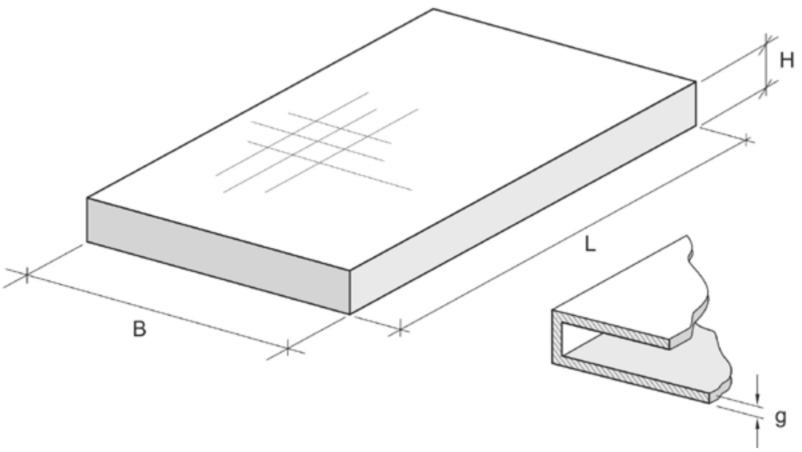

Fig. 1. Dimensions of pneumatic structural component and directions of plate anisotropy. Source: own research.

1 For example: a the internal pressure of 8 kPa the critical force in the tested component exceeds 230 N, whereas at the pressure of 20 kPa the force increases to 922 N.

In further considerations, when deriving theoretical relationships for the plate, the following simplifying assumptions are made:

- the material of the pneumatic element carries solely tensile stresses;
- a planar state of stress, whose principal directions coincide with the axes of symmetry of the structural component, prevails in the plate;
- the anisotropy of the two-phase material, i.e. rubber reinforced with fabric, was omitted, assuming mechanical properties averaged across shell thickness *g*.

Determination of stresses in plate subjected to internal pressure

A planar state of stress, whose distribution is shown in figure 2, prevails in the plate.

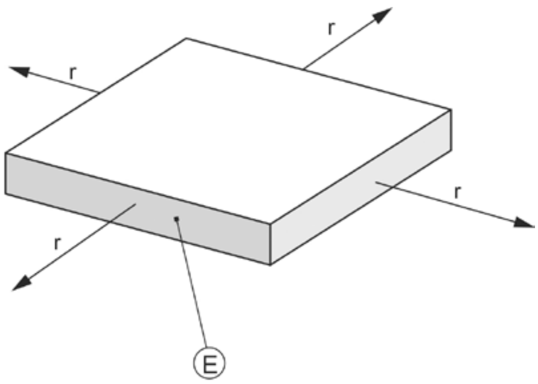

Fig. 2. Components of stress state in plate (E – component of plate). Source: own research.

The stresses amount to:

$$\sigma_1 = \frac{F}{A_1} = \frac{p \cdot B \cdot H}{(2 \cdot B + 2 \cdot H)} \tag{1}$$

$$\sigma_2 = \frac{F}{A_2} = \frac{p \cdot L \cdot H}{(2 \cdot L + 2 \cdot H)} \tag{2}$$

where: p – the internal pressure in the plate, L, H, B, g – the plate dimensions as specified in figure 1.

The safety condition for the plate's material will be determined on the basis of Huber's yield criterion and strength hypothesis:

$$\sigma_{red(H)} = \sqrt{\sigma_1^2 - \sigma_1 \cdot \sigma_2 + \sigma_2^2} \le k_r \tag{3}$$

Pneumatic element under compression(without buckling)

The compression loading scheme for the plate is shown in figure 3. For the pneumatic element subjected to compression, but protected against buckling, the maximum compressive force was calculated assuming that the shell carried solely tensile stresses which could reach the limit value of 0, i.e.

$$\sigma_p + \sigma_F = 0 \tag{4}$$

where: σ_p – the stress in the shell generated by pressure p, σ_F – the stress in the shell generated by compressive force F_c.

One gets the maximum value of the compressive force from condition (4):

$$F_c = p \cdot B \cdot H \tag{5}$$

where: p – the internal pressure in the plate, B – the width of the plate, H – the thickness of the plate.

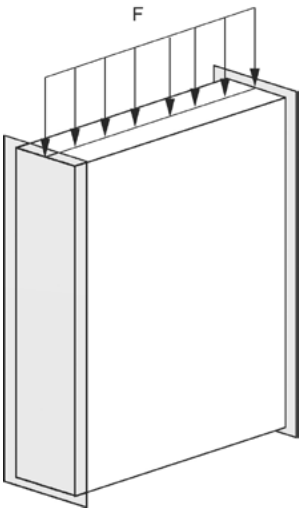

Fig. 3. Compression loading scheme for pneumatic component. Source: own research.

Pneumatic element under bending

The bending loading scheme for the pneumatic element is shown in figure 4.

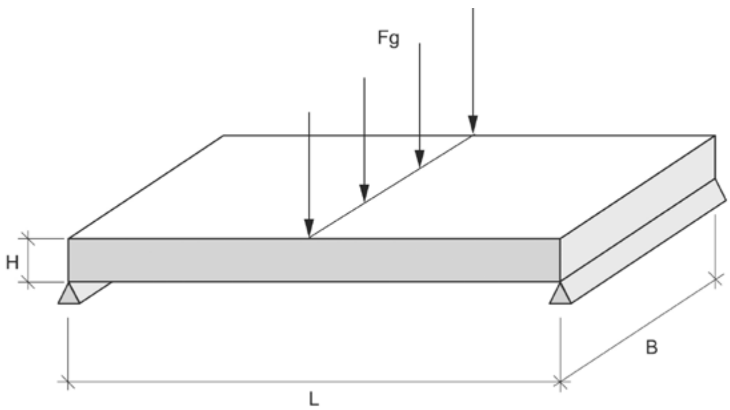

Fig. 4. Bending loading scheme for pneumatic element. Source: own research.

The following equation was used to calculate deflections:

$$f = \frac{F_g \cdot L^3}{48 \cdot EJ_z} \tag{6}$$

where: F_g – the bending force, EJ_z – internal pressure-dependent bending stiffness based on measurements, f – the maximum absolute deflection.

The unknown and difficult to determine equivalent stiffness EJ_z resulting from internal pressure can be calculated from the measured deflections. For this purpose we shall use relation (6) in the form:

$$EJ_z = \frac{F_g \cdot L^3}{48 \cdot f} \tag{6a}$$

Buckling. It is further assumed that the pneumatic component is linear-elastic. Thanks to this assumption the critical force which causes buckling can be calculated from Euler's relation:

$$F_k = \frac{\pi^2 \cdot EJ_z}{(\beta \cdot L)^2} \tag{7}$$

where: EJ_z – the equivalent bending stiffness, β – a coefficient dependent on the way of fixing the component.

The second moment of area of the pneumatic element's cross section is calculated on the basis of the dimensions given in figure 5.

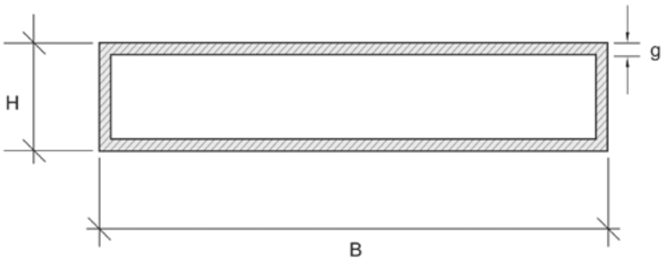

Fig. 5. Cross-sectional dimensions of pneumatic element. Source: own research.

Assuming that $H \ll B$, we shall omit the part of the second moment of area exhibited by the side walls of the element with height H. Under this assumption we get:

$$J_z \cong 2 \cdot B \cdot g \cdot \left(\frac{H}{2}\right)^2 = \frac{B \cdot g \cdot H^2}{2} \tag{8}$$

The minimum radius of gyration of the cross section is:

$$i_z = \sqrt{\frac{J_z}{A}} = \sqrt{\frac{B \cdot g \cdot H^2}{4 \cdot B \cdot g}} = \frac{H}{2} \tag{9}$$

Experimental tests

Pneumatic element. Experimental tests were carried out on a pneumatic element in the form of a rectangular prism. A mattress with flat walls was selected for the tests.

Measuring equipment. The measuring setup consisted of:
- a loading system,
- an air-compressor with maximum pressure p = 5 [MPa],
- a pressure gauge with the high measurement resolution of 0–0.05 [MPa]

The loading system was specially designed and built for the buckling testing of pneumatic elements. The system is shown in figure 10. The system enables the compression of a pneumatic element for the two ways of fixing its ends, shown in figure 6. Parts of the loading system were used as supports for measurements under bending.

Table 1. Results of measurements of pneumatic elements subjected to bending

No.	Measurement No.	Pressure p [kPa]	F [N]	f [m]	f_{cer} [m]	EJ_z [Nm²]	$E{\cdot}J_{z(sr)}$ [Nm²]	E [MPa]	E_{sr} [MPa]
1	1	8	70	0.08		50.02			
2	2	8	70	0.08	0.078	50.02	51.1	20	
3	3	8	70	0.075		53.3			
4	1	8	100	0.125		45.7			19
5	2	8	100	0.120	0.125	47.6	45.8	18	
6	3	8	100	0.130		44.0			
7	1	11.5	70	0.04		100			
8	2	11.5	70	0.035	0.04	114	100.1	39.1	
9	3	11.5	70	0.045		88.9			
10	1	11.5	100	0.075		76.2			
11	2	11.5	100	0.078	0.075	73.3	75.9	30.0	32.1
12	3	11.5	100	0.073		78.3			
13	1	11.5	150	0.125		68.6			
14	2	11.5	150	0.123	0.123	69.7	68.6	27.0	
15	3	11.5	150	0.127		67.5			
16	1	15	70	0.030		133.0			
17	2	15	70	0.030	0.030	133.0	134.7	52.7	
18	3	15	70	0.029		136.0			
19	1	15	100	0.048		120.3			
20	2	15	100	0.046	0.047	124.3	121.2	47.4	47.0
21	3	15	100	0.048		112.1			
22	1	15	150	0.086		102.3			
23	2	15	150	0.084	0.085	105.7	104.2	41.0	
24	3	15	150	0.085		104.5			
25	1	20	70	0.019		210.6			
26	2	20	70	0.018	0.019	222.3	214.5	84.4	
27	3	20	70	0.019		210.6			
28	1	20	100	0.032		178.6			
29	2	20	100	0.030	0.032	190.5	180.8	71.2	70.4
30	3	20	100	0.033		173.2			
31	1	20	150	0.065		132.0			
32	2	20	150	0.060	0.061	143.0	141.0	55.5	
33	3	20	150	0.058		147.8			

Measurement programme. The measurement programme covered measurements of the maximum absolute deflection under bending for the following pressures in the shell: 8, 11.5, 15 and 20 [kPa]. For each of the pressures the maximum absolute deflection was measured under the following loads (applied in the middle of the element length): 70, 100 and 150 [N]. Thanks to this measurement programme the effect of the internal pressure on the bending stiffness of the element, and the linearity of the deflections as a function of the load were assessed. The measurement programme for buckling included tests of the stability of the shell element for the three ways of fixing the shell's ends, shown in figure 6. The programme was carried out in the loading device.

No experiment is needed for the case of element compression (without buckling) since the maximum compressive force with which the pneumatic element can be loaded is calculated from equation 4. Also no experiment is needed to determine the stresses in the shell since their values can be theoretically determined. The stress intensity level in the shell material was not taken into account in further considerations since the adhesive bonds were the weakest elements. The experimental pressures were such that the shell was considerably stiff without losing its air tightness.

Bending. Shell bending strains were measured to experimentally determine the bending stiffness of the component and the longitudinal modulus of elasticity of the material depending on the pressure.

The measured maximum absolute deflections under bending are presented in table 1, which also contains values of mean equivalent bending stiffness $E \cdot J_{z(sr)}$ for different pressures and elasticity modulus (E_{sr}) values obtained from this experiment, also depending on the pressure.

Buckling. Critical buckling forces were measured for three ways of fixing the ends of the pneumatic element. The fixing cases are shown in figure 6.

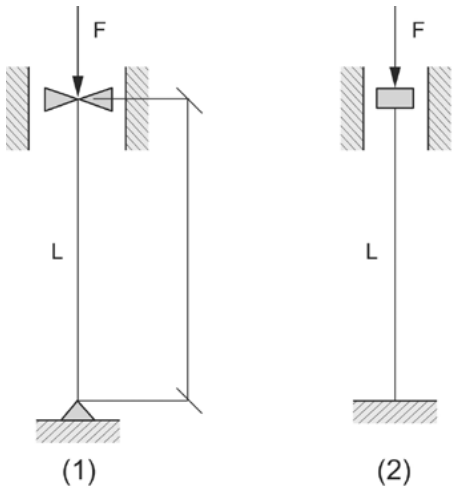

Fig. 6. Ways of fixing element ends, Source: own research

The tests were carried out at different internal pressure values. Similarly as for bending, the following internal pressure values were adopted: 8, 11.5, 15 and 20 [kPa]. The measurement results are presented in table 2.

On the basis of the results given in table 1a graph of $E \cdot J_{z(sr)}$ versus internal pressure *p* was drawn. The graph is shown in figure 7.

Table 2. Results of measurements of critical force at pneumatic component buckling

No.	Fixing case	β [kPa]	Pressure p [kPa]	Critical force F_{kr} [N]	Mean critical force $F_{kr(sr)}$ [N]
1	1		8	240	
2	1		8	226	235.7
3	1		8	235	
4	1		11.5	410	
5	1	1.0	11.5	390	387
6	1		11.5	360	
7	1		15	660	
8	1		15	620	617
9	1		15	572	
10	1		20	980	
11	1		20	925	922
12	1		20	862	
13	2		8	556	
14	2		8	450	476
15	2		8	423	
16	2		11.5	860	
17	2		11.5	800	790
18	2		11.5	710	

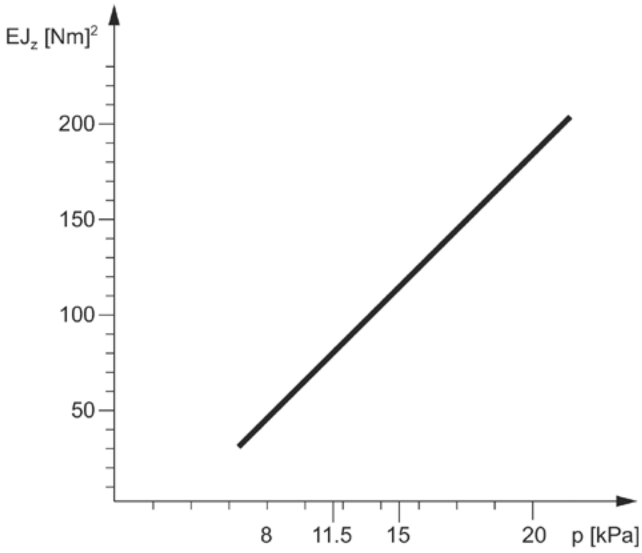

Fig. 7. Bending stiffness versus pneumatic element internal pressure. Source: own research.

The relationship between deflections and the loading force is shown in figure 8.

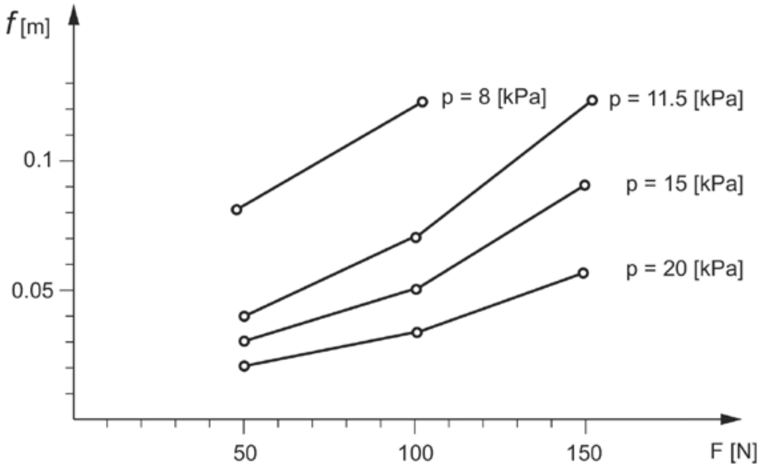

Fig. 8. Relationship between pneumatic element deflections and loading force at bending. Source: own research.

It appears from table 2 that the full range of buckling loads was implemented only for the two-hinged fixing. In the case of the other ways of fixing, the loading programme could not be implemented due to the too low internal pressures, whereby the element would deform as a result of compression before buckling occurred. For this reason only one graph illustrating the relationship between the critical force and internal pressure was drawn. The graph, based on table 2, for the first way of fixing the element's ends is shown in figure 9.

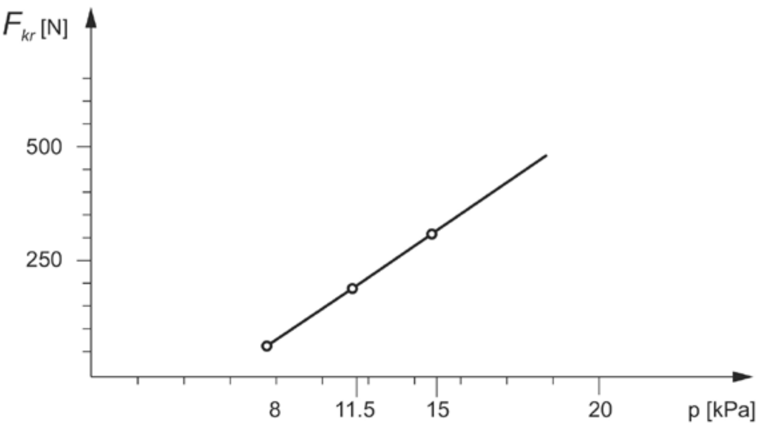

Fig. 9. Critical force versus pressure *p* (acc. to Euler) for two-hinged fixing. Source: own research.

Conclusions

- The bending stiffness of the pneumatic element is a linear function of internal pressure.
- In the case of the two-hinged fixing, the critical force is a linear function of pressure.

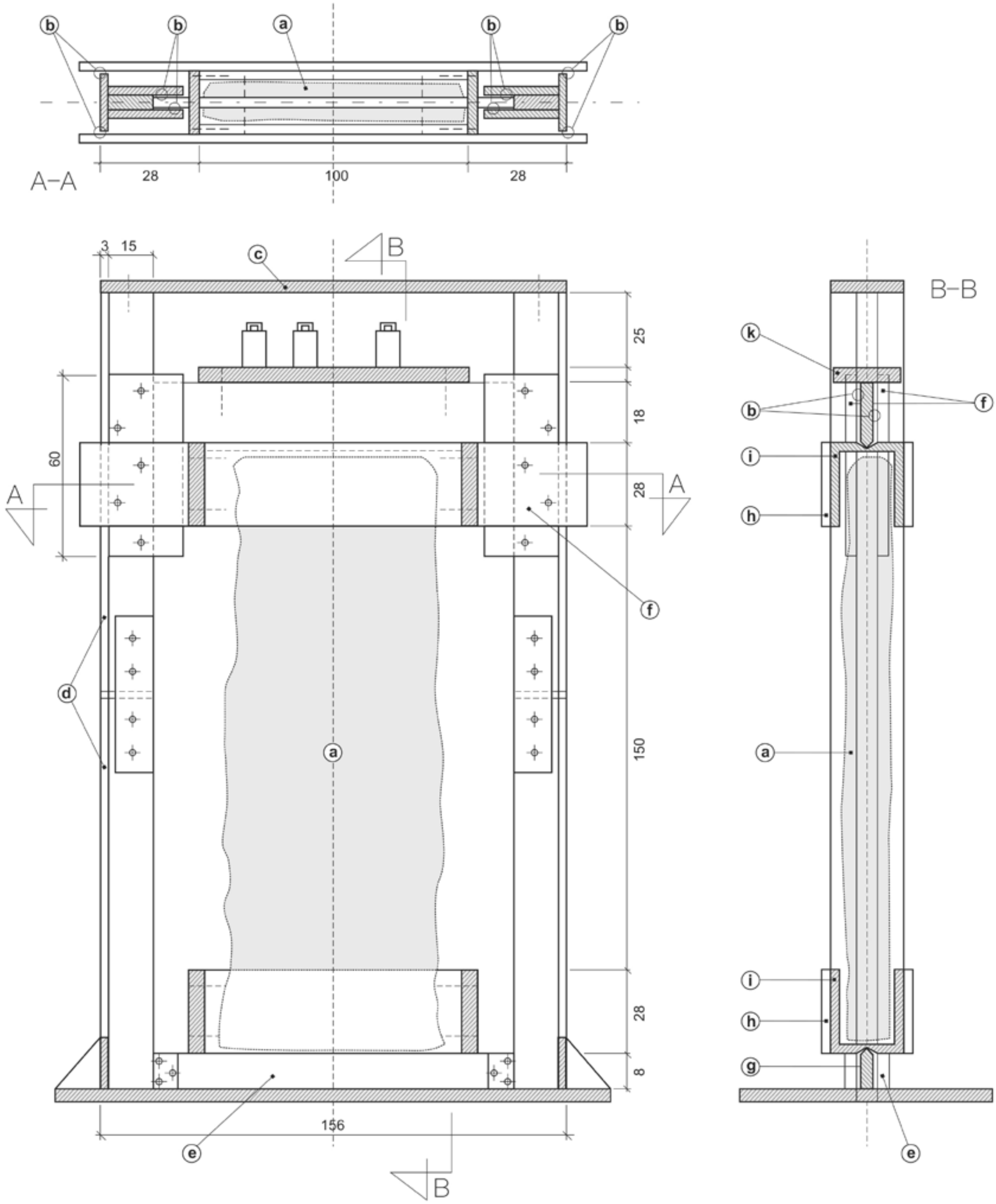

Fig. 10. Loading system (a – Inflatable mattress, b – Sliding gaps, c – Stiffener plank, d – Members joined together at mid height, e – Fixing element, f – Guides, g – Permanent element, h – Screwed-on plank, i – Box, k – Moving element). Source: own research.

Final conclusions

pt. 1. The applicability in the house building industry, of the spatial pneumatic structures whose principal structural component is a flat pneumatic element used to construct the load-bearing walls and floors of dwelling

modules, has been indicated and demonstrated considering the light weight of the spatial pneumatic structures, the ease and speed of their assembly and their computationally and experimentally proven advantageous load-bearing properties.
pt. 2. The critical force has been shown to be linearly dependent on the internal pressure in the flat pneumatic element, whereby its stiffness can be increased by increasing the cross section or the pressure. Under bending a similar dependence occurs between the bending stiffness and the internal pressure.
pt. 3. The relations presented in the theoretical part form the basis for developing models of various flat pneumatic elements (e.g. ribbings) and considering different ways of joining and supporting them.
pt. 4. It follows from pts 2 and 3 that it is necessary to build the components of the pneumatic structure, taking the results of this study into account, test them in the specified conditions and verify their dimensions and internal pressures. On this basis a prototype or model of the spatial pneumatic structure in the form of a dwelling module should be built.
pt. 5. On the basis of the results of this study (pt. 2) and the results obtained as specified in pt.4 it will be possible to develop computations and guidelines for designing spatial dwelling structures.

Recapitulation

1. It seems that the above research should be continued. As the principal directions of this research one can mention the following:
   1.1. The theoretical formulation of the model.
   1.2. The experimental testing of the model and finally, of the actual facility.
2. Moreover, from another point of view the research work can be divided into:
   2.1. Architectural work (concerning the architectural function and form of the dwelling facilities). Because of the different character of the pneumatic structures, in comparison with the currently used structures, one can consider, on the basis of the geometry of polyhedrons, the use of other than cuboidal, spatially-stable forms of the dwelling modules.
   2.2. Structural-constructional solutions (the formulation of assumptions concerning the geometric parameters of the structures).
   2.3. Materials strength investigations for different pneumatic plate models. The investigations should cover both structural calculations and experimental tests.
   2.4. Materials research (concerning the technology of manufacturing a proper material, and the testing of material properties).

Summing up, considering that no studies on this subject, which would cover both its scientific and utilitarian (the very wide range of potential applications) aspects, can be found in the literature, this research work should be continued.

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Płaskie elementy pneumatyczne i możliwość ich zastosowania w konstrukcji obiektów mieszkalnych awaryjnych systemów budownictwa

Streszczenie: Praca składa się z dwóch części. Pierwsza z nich jest opisowa, druga zaś jest sprawozdaniem z przeprowadzonych badań doświadczalnych. Generalnie, podjęto próbę określenia zakresu tematyki badawczej, której wynikiem byłoby określenie i wyznaczenie wszelkich parametrów dotyczących zarówno własności stosowanego materiału, jak i parametrów geometrycznych elementów konstrukcyjnych pneumatycznych obiektów mieszkalnych.

W szczególności opracowano i wykonano:

- teoretyczną ocenę nośności i sztywności wybranych elementów pneumatycznych w zależności od ich wymiarów, ciśnienia wewnętrznego, warunków zamocowania i podparcia,
- weryfikację doświadczalną otrzymanych wyników.

Przedstawiona praca ma charakter rozpoznawczy i stanowi podstawę do zaprojektowania i wdrożenia oryginalnych rozwiązań technicznych, konstrukcyjnych i architektonicznych w zakresie zastosowań przestrzennych struktur pneumatycznych do systemu awaryjnego.

Nadmienić trzeba, że w znanej literaturze przedmiotu brak podstaw teoretycznych do projektowania takich struktur, których zasadniczym elementem konstrukcyjnym jest płaski element pneumatyczny.

W budownictwie nie stosuje się dotychczas takich konstrukcji. Przykład rozwiązania przestrzennej struktury mieszkalnej został opatentowany pod nazwą „Obiekt mieszkalny”, (patent nr 131 528, z dnia 18.04.1988).

Słowa kluczowe: lekkie konstrukcje nośne, konstrukcje pneumatyczne, przestrzenne struktury pneumatyczne, obiekty mieszkalne