Post-Tensioned Modular Inflated Structures

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Pneumatic structures are usually considered as inalterable, with predetermined features, e.g. shape etc. According to this approach, they cannot be easily rebuilt or modified. Application of techniques current in other sectors of construction industry leads to the structures that are much more flexible and adaptable.

1 Introduction

The prestressing technique was applied to concrete and steel constructions in first decades of 20th century. It appeared after a period of development of these constructions, and its usage is obvious and common at present. Yet in reference to pneumatic constructions, the conception of prestressing appeared at the beginning of their development. The first known documentary evidence of the conception to use structural pneumatic elements comes from engineer Joachim A. Sumovski. He obtained, in 1893, an American patent on air-inflated structures [1]. One of the drawings included in patent specification presents the structure that obtains its shape and loading capacity as a result of prestressing, Fig. 1.

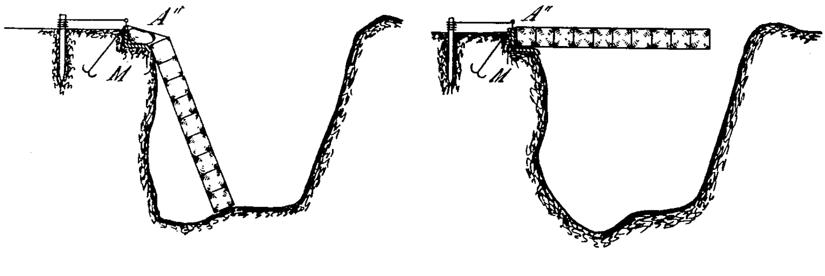

Fig. 1. An example of air-inflated structure invented by J.A. Sumovski

E. Oñate and B. Kröplin (eds.), Textile Composites and Inflatable Structures, 221–239.

However in air-supported structures, particularly of large span, strengthening cables are nowadays often applied [2] – prestressing is not yet obvious in air-inflated structures.

Another, well-known structural concept, which provides with many advantages in terms of creating structures – is the use of repeatable, modular units, that can be assembled in a larger, complex structure. The spectacular example of application of repeatable air-inflated units for constructing a large structure – was the pavilion of Fuji Group, at Expo '70 exposition in Osaka [3].

The advantages of modular structures are especially exposed, when units of relatively small dimensions are used. This allows constructing structures of various shapes, while limited quantity of different units are applied. The units can be used repeatedly many times. Shape of the structures created in this way is limited only by topological restrictions of division of considered surface. This applies in particular to the shell structures.

Post-tensioning is a way of splicing small elements but also a way of shaping the structure. Coupling of these operations raises the efficiency of solution. Because of specific properties of pneumatic structures, suitable technical solutions are required, especially concerning supplying the elements with air, stabilization of their shape as well as method of connection.

2 Modular Air-Inflated Elements Applied to Shell Structures

2.1 Principles of Composition

Depicted structures present a class of spatially curved surface girders. Their rigidity and loading ability are strongly related with the shape. Spatial curvature itself, is not a permanent, generic feature of the structure (as it is in concrete shells for example), but is achieved and maintained by means of post-tensioning, causing very large initial deformation. Thus, the final shape and properties of the structure are function of initial configuration and the course of post-tensioning process.

Internal structure of modular air-inflated shells distinguishes them from other air-inflated structures and from other shell structures. They consist of the following basic elements:

- air cushions (main modular elements)
- tension cables
- cross-braces (optional)

Air cushions and cables appear in shells of all types, while cross-braces only in the shells with increased structural height [4]. After assembling, structure forms complete roofing and does not require any additional membranes to cover space. General view and components of an exemplary structure is shown on Fig. 2.

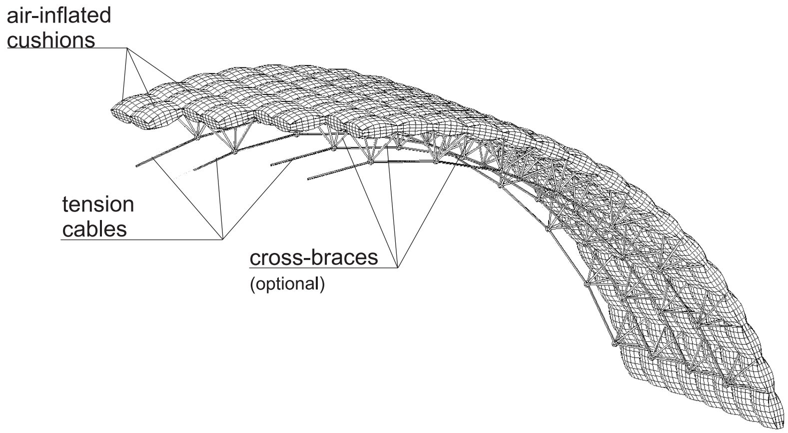

Fig. 2. Composition of modular air-inflated shell

2.2 Structural Components

Air cushions

Pneumatic modular elements have a form of cushions shaped in order to fit geometrical constrains of the prospective surface. Basic shapes are: rectangle, square, rhomb, hexagon and triangle. Following conditions must be fulfilled in order to enable effective application of modular system:

– shape of the cushions must correspond with final shape of the structure; it is obvious that the usage of as few varying shapes as possible is profitable
– elements must be small enough in relation to the final structure, to form a smooth, easily deformable surface (at least ten times smaller); additional criteria can be also applied, such as easiness of in-site manipulation e.g. one workers should be able to carry the cushion
– the connections between the elements have to assure their suitable integration as well as continuity of transmission of internal forces
– the cushions should be suitably equipped with guides allowing the usage of post-tensioning cables

Other components

Bar members (i.e. cross-braces) are optional – they appear only in some types of shells. These additional bars are used in order to increase the structural height. They can be made of any lightweight material capable of carrying compression, like steel, aluminum, wood or composite. Naturally, closed sections (tubular) are better than the others, for this purpose. Connection of bars and cushions must prevent damages (e.g. by means of strengthened pockets).

Post-tensioning cables are always placed at the internal side of curved shell. In case of anticlastic shells, cables are placed in two layers – at the opposite sides of the shell. Direction of cables in each layer corresponds with the curvature of the shell, Fig. 6. The cables can be placed directly below the cushions or below cross-braces. In both cases the cable should be able to slide freely through the nodes. Both, fiber ropes (made of natural or man-made fibers) and wire ropes can be used as post-tensioning cables. It is significant that the cushion was protected from damages caused by ropes, e.g. by means of protective jackets.

2.3 Transmission of Forces

After completion, modular elements must transmit internal forces induced in the structure. It is possible due to the compression of cushions' sides (touching each other) and tension of their external cover and post-tensioning cables, Fig. 3. Thus, the way of assembling the cushions must ensure a full contact of side surfaces and continuity of external cover.

These basic principles allow setting a geometrical configuration of the shells of various size and shape, designed for various purposes.

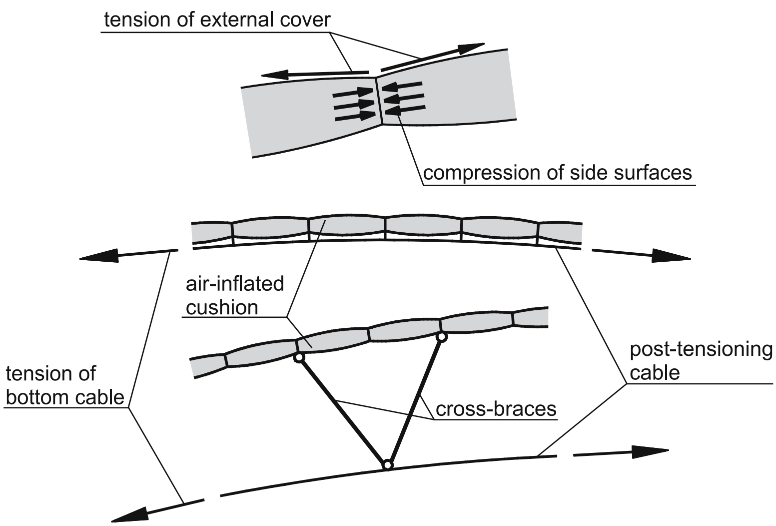

Fig. 3. Transmission of forces in modular air-inflated shells

3 Application of Post-Tensioning and Self-Erection

The structure is stabilized by means of post-tensioning. This process induces internal forces that are shown on Fig. 3. Distribution of these forces is invariable during exploitation, though their values can change. Alteration of forces' direction effects in destruction of the structure – in consequence of opening of the gaps between cushions or "compression"of their external cover, Fig. 4.

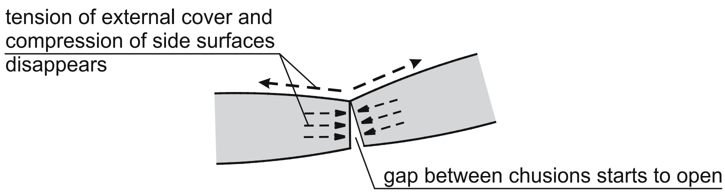

Fig. 4. Failure mode of the shell

There are two ways of realizing the post-tensioning procedure:

– structure is post-tensioned and erected simultaneously (self-erection)
– post-tensioning is applied to previously erected structure

3.1 Self-Erection Procedure

In that case, the flat structure is assembled at ground level as a near mechanism. It is stabilized and finally shaped by means of self-erection. This process unifies operations of post-tensioning, erection (i.e. construction) and spatial curving of the structure. The essence of the process is the introducing into the structure forces that cause its large deformation [5]. In practice, the process starts simply with a shortening of the bottom cables. The cables are attached to the fixed supporting points while going through all the other joints to the opposite, mobile, supporting points.

As a result – supporting points are brought closer to each other. Thus the deformation is introduced to the structure and it starts to erect. The process is continued till required position is obtained. Then the cables are fixed in the mobile supporting points. Fig. 5 presents successive stages of self-erection process.

Air-inflated shell can be post-tensioned either in one direction or in two directions. Unidirectional post-tensioning is applied in order to get structures with zero Gausian curvature (cylindrical), while bidirectional - when structures with negative Gausian curvature (anticlastic) are required, e.g. hypar surfaces, Fig. 6.

Bidirectional post-tensioning is performed successively. At the beginning, cables of the first direction are tensioned to 50–60 % of assumed value. Then

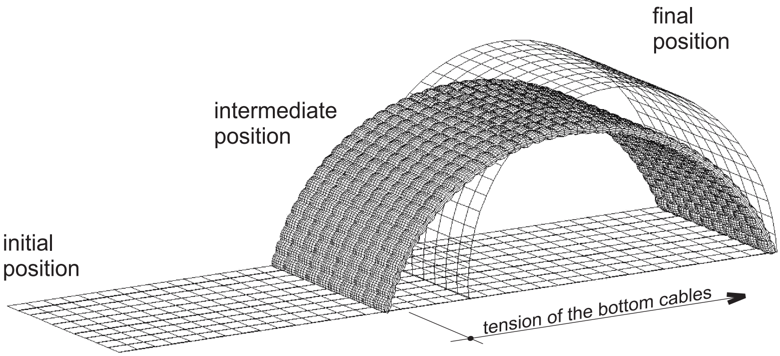

Fig. 5. Scheme of self-erection procedure

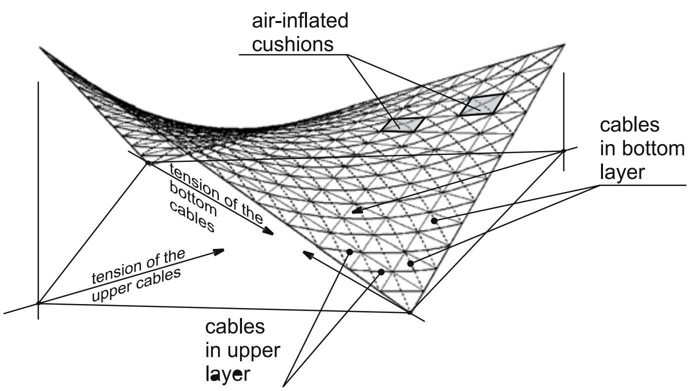

Fig. 6. Bidirectional post-tensioning of air-inflated shell

cables of the second direction are tensioned to the same value. Finally, the cables are alternatively rectified, to reach requested values.

3.2 Post-Tensioning Applied to Completed Structure

Another way of assembling is to put cushions in position one by one – as in an igloo and then tension the cables to stiffen the structure. In that case, shell must be shaped as a self-stable before post-tensioning is performed. Certainly, scaffoldings can be used, however, this overthrows the whole system.

Structures with positive Gausian curvature (synclastic), surfaces of revolution in particular, can be achieved in that way. Fig. 7 presents such a structure, shaped as a hemisphere, made of hexagonal elements.

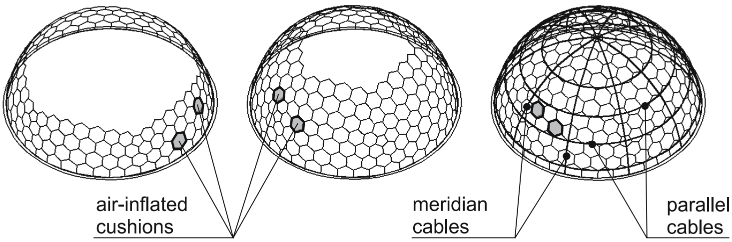

Fig. 7. Construction of synclastic air-inflated modular shell

4 Adjustment of Rigidity and Hardening Systems

4.1 Structures with Variable Rigidity

Curvature of air-inflated shells formed in self-erection process can be controlled by means of changing their rigidity along the span [6]. It is an effective way of shaping this kind of structures, which allows fulfilment of the requirements. Initial stiffness of inflated shell is defined mostly by its structural height. The change of height causes the change of stiffness. This can be achieved in two ways:

- either by use of additional rods, i.e. cross-braces, moving tension cables down from the cushions
- or by change of cushions' thickness

Figure 8 presents those two methods.

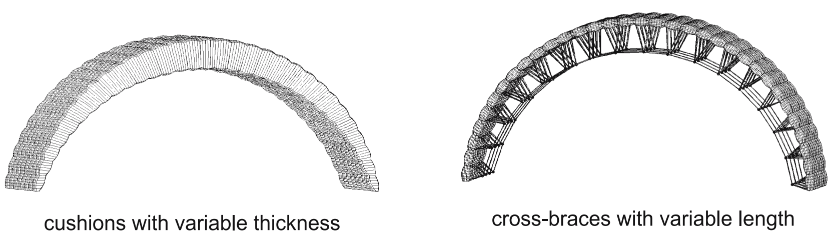

Fig. 8. Methods of rigidity alteration in modular shells

Two compared shells, of the same initial length and subjected to the same upthrust, i.e. nearing of supports, but with various, variable rigidities, demonstrate distinctly different final geometry. If the rigidity of the shell is increased in the central part – the curvature is smaller in the center than in peripheres (structure is more flat). On the other hand – the curvature is smaller on sides, when rigidity is decreased in the central part of the shell (structure is more scarped). Fig. 9 presents a comparison of shapes of cylindrical shells with variable rigidity. More sophisticated shapes can be achieved when rigidity is changing according to a parametric function.

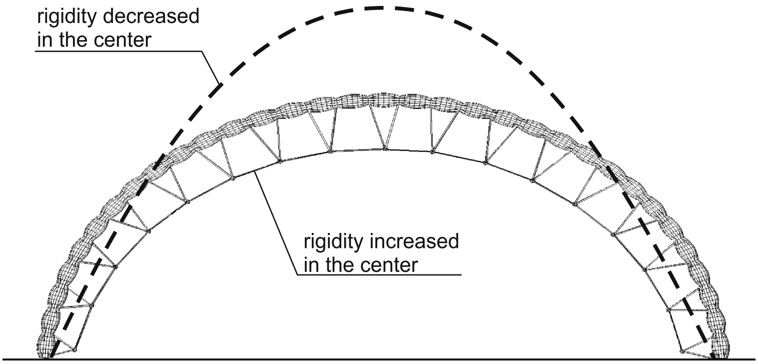

Fig. 9. Comparison of shells with variable rigidity

4.2 Adaptable – Hardening Structure

Variation of rigidity allows constructing a structure that actively adapts to external loadings. If the internal lever arm increases together with increasing external loadings – deformations increment slowly. Load–deformation relation in this case is an exponentially growing function. If the internal lever in the structure can be self adjusted in order to find position of equilibrium, then the structure reveals a "hardening"characteristic. In numerous situations this specific type of structures is more advantageous than any other, with a linear response. An example of hardening system is described in [7]. Its application in pneumatic shells [8] is shown on Fig. 10.

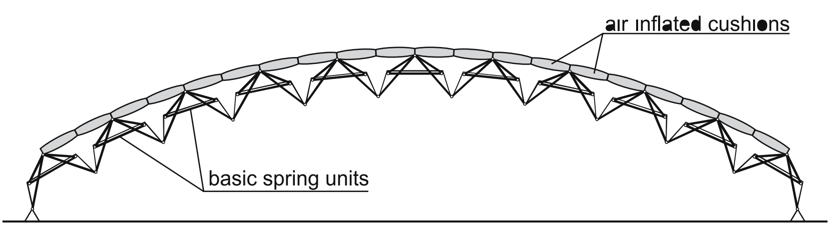

Fig. 10. Example of air-inflated hardening structure

5 Technological Concepts

5.1 Air-Inflated Cushions

The cushions are the basic components of the shell. The air supplying system described below maintains internal pressure. Cushion is usually a flat element – its thickness is smaller than dimensions in plane. Two main surfaces (upper and bottom) and several side surfaces can be distinguished in the cushion. It is generally made of soft textile or foil, suitable for pneumatic structures.

The cushions are equipped with elements that allow attaching a tension rope. These are the flexible hoops enabling the rope to slide easily. The rope is dragged through the hoops during assembling. The hoops are placed at the cushion's corners, on one or on both main surfaces (e.g. for hypar shells).

If the cross-braces are to be placed in the structure, strengthened pockets are made in the cushions. Strengthening prevents damage of soft fabric caused by bar edges.

Cushions with flaccid main surfaces must be equipped with internal elements ensuring flat shape after inflation. Fabric diaphragms (with openings) or set of threads can be applied in this case. These elements are not necessary if both main surfaces are made of rigid panels. Fig. 11 presents a general scheme of the cushion entirely made of fabric.

For the structures with variable rigidity, cushions with variable thickness can be prepared. Main surfaces of such a cushion are not parallel and side surfaces have various width, as shown on Fig. 8.

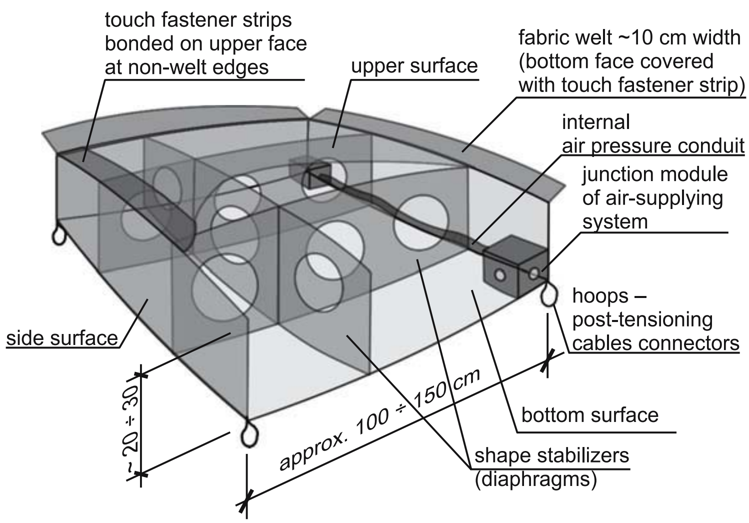

Fig. 11. Internal structure of air-inflated cushion

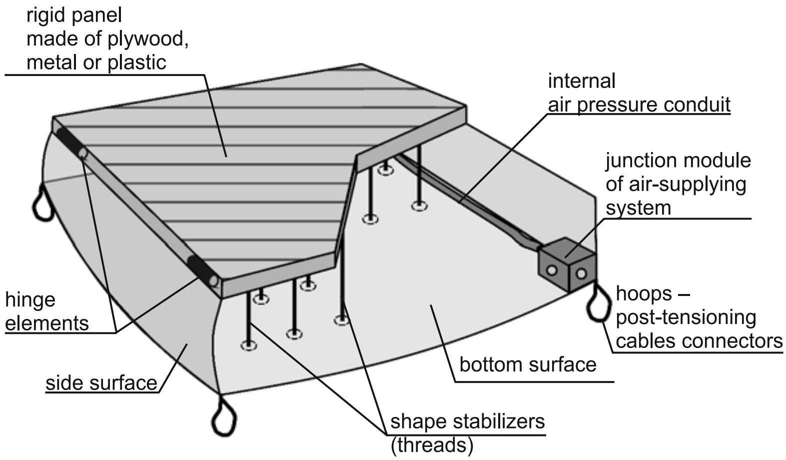

Fig. 12. Internal structure of semi-rigid air-inflated cushion

For some applications, semi-rigid cushions are necessary. In this case, one or both main surfaces can be made of rigid panels (metal, plywood or plastic), Fig. 12. Side surfaces are always made of textile, to assure a proper contact between cushions after assembling.

5.2 Connections of Cushions

There are two points of connection:

- connection of main surfaces
- connection of side surfaces

Side surfaces are connected by means of direct clamping, as it is shown on Fig. 3. In order to ensure a proper connection, contact of surfaces cannot be restricted in any way (e.g. by protruding rigid panels, cross-braces or connectors of air supplying system).

Connection of main surfaces should assure continuity of transmission of tensile forces in the shell, in all directions. Additionally, if the shell is used as a cover protecting against weather conditions, these connections should assure the tightness of the shell.

If the main surfaces of the cushion are soft, a convenient type of connection is "touch fastener" (e.g. Velcro). Welts with a bottom face covered with fastener strips are placed along some of cushion's edges. The edges at the reverse sides of the cushion are also covered with touch fastener strips. The continuity and tightness of the shell can be easily obtained during assembling, Fig. 13.

Another feasible connection is a "zipper"– a wire strand or flexible bar dragged through the small, tight-fitting eyes placed along edges, Fig. 14. Both

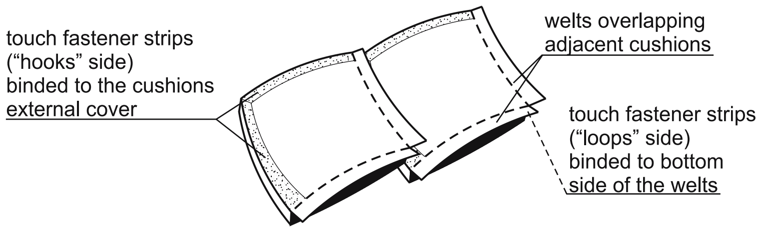

Fig. 13. Connections of soft cushions – touch fasteners

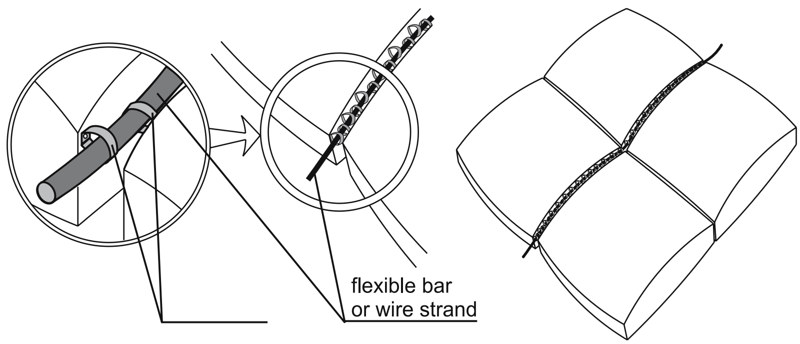

Fig. 14. Connections of soft cushions – "zipper"

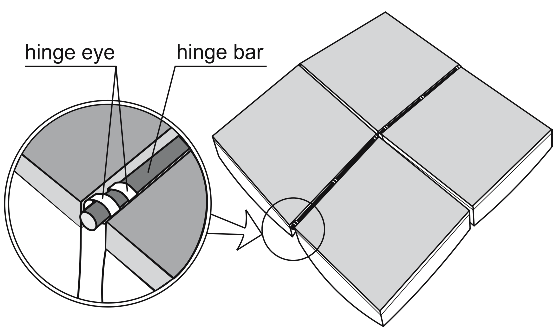

Fig. 15. Hinge connections of semi-rigid cushions

concepts can be used together, when high value internal forces are induced in the shell. In that case, the "zipper" transmits the forces, while touch fasteners are tightening the cover.

Connection of semi-rigid cushions can be formed as a two-piece hinge, completed during assembling, Fig. 15.

5.3 Air Supplying System

Air-inflated shell can be exploited only, when equipped in an efficient air supplying system. This system should assure unfailing inflation and deflation of cushions and maintenance of internal working pressure. It should be foolproof.

An exemplary solution is a system integrated with cushions. It consists of the web of internal pressure conduits, placed inside cushions. These conduits are linked by means of self-tightening, male connectors. Junction modules are situated at side–bottom corners of the cushion. This facilitate coupling eliminates any external part of the conduits. Air pressure inside the conduits is significantly higher than the working pressure in the cushions. The mentioned above junction, contains control unit (valves) regulating internal pressure. When the pressure decreases, the valve opens and air from the conduit is forced inside. When the pressure increases, e.g. in the case of elevated temperature, the valve ejects needless air outside. The same function is used for deflation.

It is possible to use special explosive cartridges for very quick (instant) inflation. In that case, a suitable socket is used in the junction of air-supplying system. The cartridge, placed in this socket, can be detonated manually or by remote control. Explosion products fill the cushion and the control valve maintains the pressure. Fig. 16 presents a functional diagram of junction module in the air supplying system.

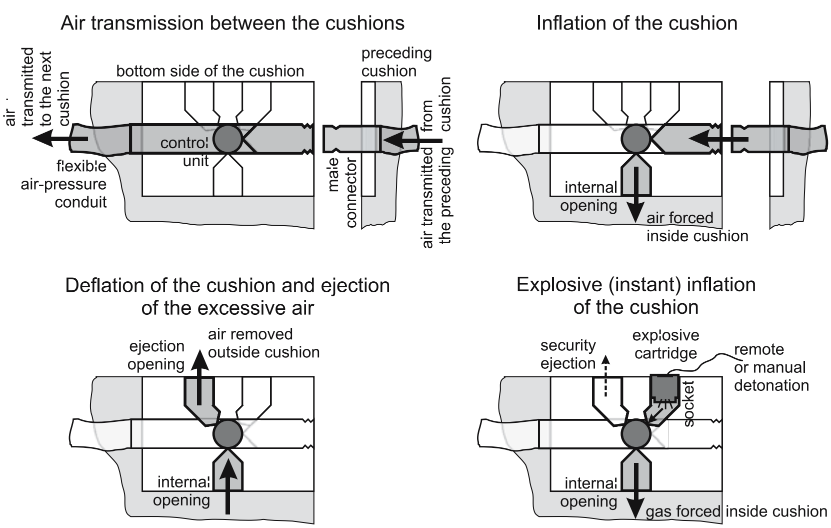

Fig. 16. Functional diagram of junction module in the air supplying system

6 Examples of Application

Modular inflated shells are suitable for wide range of applications. Some examples given below are aimed to emphasize general concepts rather then describe particular implementations. These shells can be successfully combined with many other well-known types of structures.

6.1 Cylindrical Shells

The simplest possible shape of modular air-inflated shell is a cylinder. This can be used directly for some applications, or as a part of a bigger, complex structure. However, even in this case, structure can be constructed in various ways. This can be composed only of cushions and cables, Fig. 17, or with optional use of cross-braces, Fig. 18 and Fig. 19.

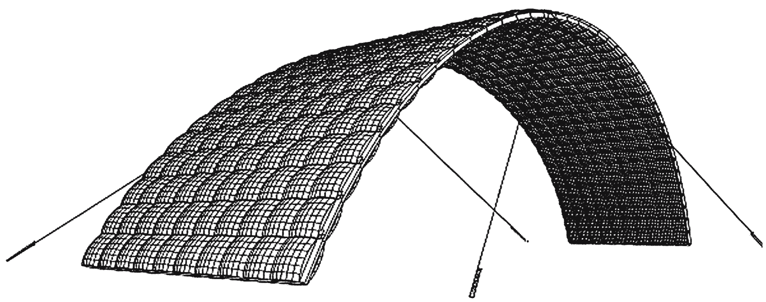

Fig. 17. A simple cylindrical shell composed only of cushions and cables

Cross-braces can be placed inside the structure or in reverse position, over cushions, in order to enlarge internal space, Fig. 18.

For a specific architectural effect, semi-rigid cushions are very promising. The external rigid panel can be made of translucent or painted plastic and some printed patterns can be added, Fig. 19.

6.2 Construction Site Shelter

In many cases, the construction site should be prevented from the weather conditions. It concerns, for example, concrete works as well as earth works. An exemplary structure is presented on Fig. 20. It consists of the three simple cylindrical shells that form a shelter over rectangular area. Exactly the same structure is suitable for sport facilities, e.g. tennis court.

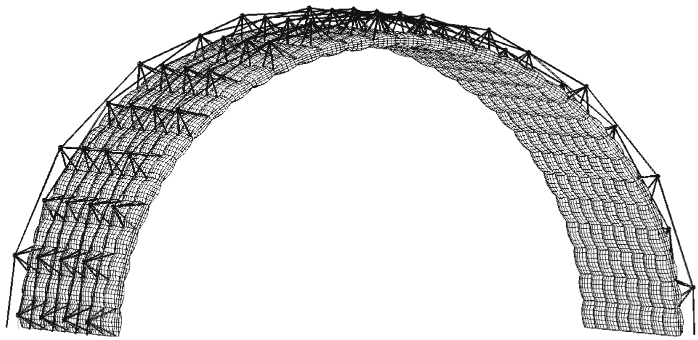

Fig. 18. Cylindrical shell with cross-braces placed in reverse position, over cushions

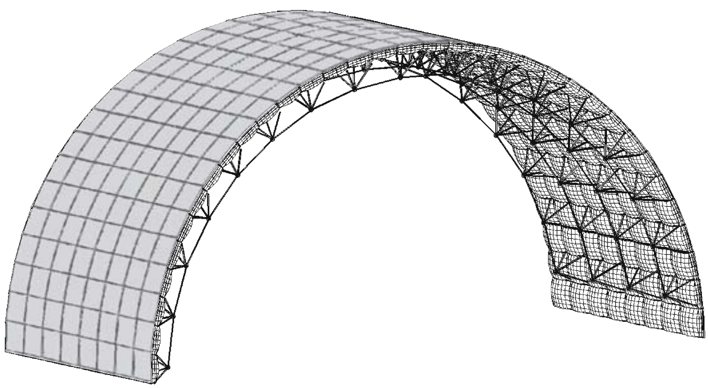

Fig. 19. Cylindrical shell composed of semi-rigid, translucent cushions

6.3 Multiple Hypar Roof

Interesting shapes can be obtained as a result of bidirectional post-tensioning. A single hypar surface, as shown on Fig. 6, can be multiplied to form a complex structure, Fig. 21. This is a good solution for itinerant theatre troops, temporary markets, exhibitions etc.

6.4 Deployable Inflated Bridge

Easily assembled and quickly erected structures, as described above, are predestinated for applications in military bridging systems. In this case the bridge

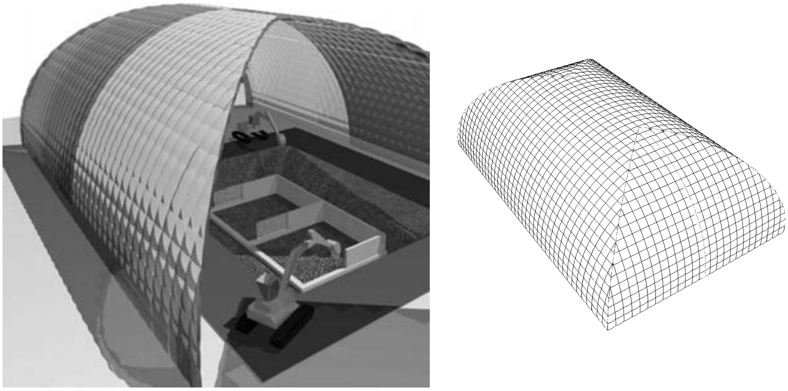

Fig. 20. General view and scheme of construction site shelter

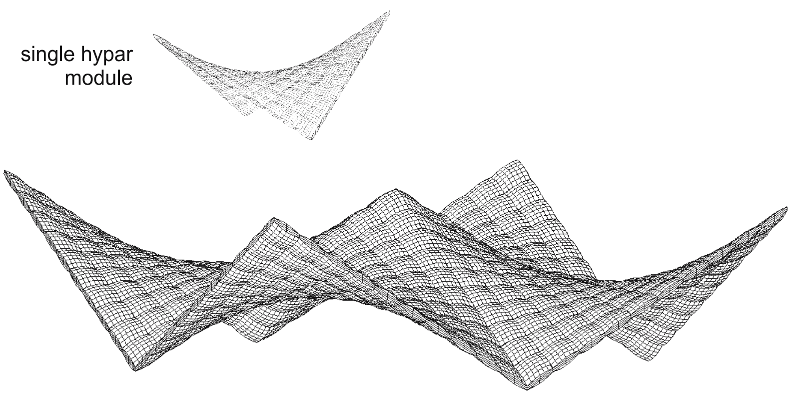

Fig. 21. Multihypar structure composed of four modules

should be launched in short time, with reduced number of in-site operations. The stowage space required for transportation should be reasonably small.

The idea to apply air-inflated elements for structural systems of portable bridges appeared at early stage of development of pneumatic structures, in sixties. Beam-type elements were tested in these early studies [9]. However, adoption of such elements caused some problems with wrinkling collapse under concentrated load. Another disadvantage of these structures is strictly predetermined span of the bridge, which cannot be changed after manufacturing. Problems recognized in beam-type bridges can be avoided by means of applying modular, post-tensioned structural systems [10].

Self-erecting inflated structures applied to deployable bridge

Deployable bridge can be constructed as a narrow sector of modular air-inflated shell. Use of semi-rigid cushions is necessary in this case, as they form a carriageable surface of the bridge. The same principles of shaping as described for modular inflated roofing are valid. Some exemplary configurations presented here are named as:

– type 1, which consists of cushions with constant thickness and cross-braces
– type 2, which consists of cushions with variable thickness
– type 3, which is basically a type 2 with modified method of deployment

Some main features are common for all these types. Rigidity of the structure is always increased in the center. Rigid panels are hinge connected on all edges. Bottom joints allow that cable is freely sliding through. A transverse steel pipe is fixed to the terminal cushions. It couples the cushions in order to properly support the structure on the ground and allows fastening of bottom cables. Air-supplying unit is placed in the transportation vehicle. Inflation by means of explosive cartridges is particularly useful in these applications.

Even after assembling, the modular inflated bridge is not an inalterable structure. The span of the bridge can be easily adjusted to the obstacle's size, simply by means of insertion or removal of required amount of cushions. This operation can be done without disassembling whole the structure, however it requires a modified construction of cable connectors.

Loading capacity of the bridge can be adjusted by means of changing its structural height and value of post-tensioning force.

Deployable inflated bridge – type 1

Deployable inflated bridge of type 1 consists of:

– rectangular semi-rigid cushions of constant thickness
– cross-braces arranged as a half of octahedron
– bottom chord (rope)

Figure 22 presents principles of composition of the structural system. Cross-braces are longer in the center and shorter in peripheries in order to adjust rigidity of the bridge. Cross-braces can be placed below every row of cushions or every second row – according to the track width and considered loadings.

General principles of assembling of the type 1 bridge are similar to those applied for self-erected roofing structures. Assembling of the cushions starts on the ground at the reverse position. Then, the cross-braces and the bottom cable are placed. The next step is to inflate cushions and rotate the structure upside–down. Then, the structure is self-erected by means of tension of the bottom cable. The last two steps can be done also in reverse order. Finally, the bridge is placed over the obstacle.

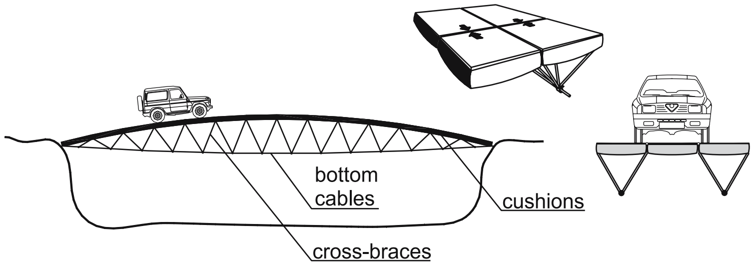

Fig. 22. Composition of deployable inflated bridge – type 1

Deployable inflated bridge – type 2

In general, composition of deployable bridge of typ 2 is the same as for the bridge of type 1. The main difference is in use cushions with variable thickness, instead of cross-braces, Fig. 23. Sequence of assembling is the same as for the bridge of type 1.

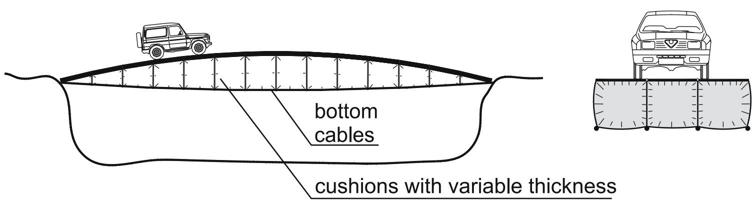

Fig. 23. Composition of deployable inflated bridge – type 2

Deployable inflated bridge – type 3

Deployable inflated bridge of type 3 is actually a bridge of type 2 with modified method of deployment. The idea is derived from the well-known children's toy "inflated tongue".

The bridge is pre-assembled, packed into a bundle and transported on a suitable vehicle. Assembling procedure starts with completely deflated and rolled set of cushions, Fig. 24.

With progress of inflation, the bridge begins to unroll. At this stage the structure reminds a "scorpion's abdomen", Fig. 25. The post-tensioning of the bottom chord starts together with inflation. This allows stabilizing the structure.

Completely inflated structure is placed over the obstacle and transportation vehicle is moving off the passage place, Fig. 26.

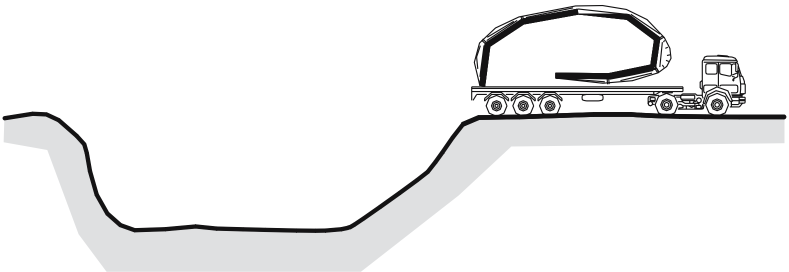

Fig. 24. Inflated bridge – type 3, bundled for transportation

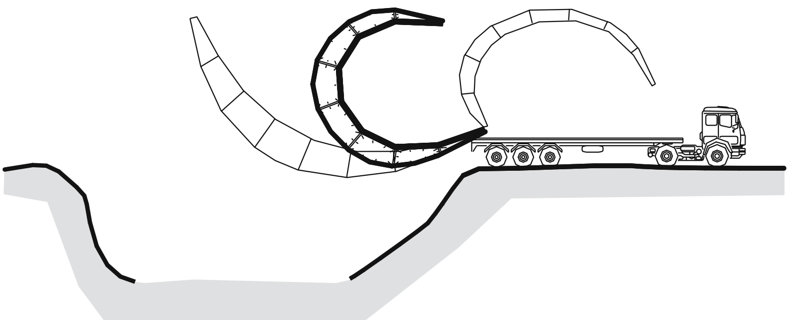

Fig. 25. Deployment of inflated bridge – type 3 ("scorpion's abdomen" position)

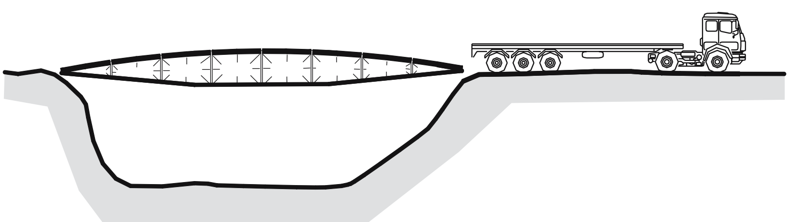

Fig. 26. Inflated bridge – type 3, ready to use

Described above, structural system for deployable bridges, exploits all advantages of air-inflated modular structures together with self-erection as a principle of shaping and erecting. This is a convenient solution for constructing bridges over precipices and rivers, in military and emergency applications.

7 Conclusive Remarks

Application of modular inflated elements to shell structures eliminates many disadvantages of air-supported structures as well as non-modular air-inflated structures. The span and (with some restrictions) shape of the structure can be determined just at the assembling. There is no need to use different structures for various purposes – many geometrical configurations can be reached. Modular inflated shell is a structure based on the idea of self-erection - a process that unifies post-tensioning and erection. Due to internal fit-out, the structure can be easy maintained. This type of structures can be used for many military and civil applications, where a fast assembled and adaptable solution is required.

References

1. Sumovski JA (1893) Tubular structure filled with gaseous fluid. US Patent 511 472
2. Geiger DH, Majowiecki M (1977) Acier-Stahl-Steel 9:281-288
3. Kawaguchi M (1993) A few nonlinear topics in structural design. In: Hangai Y, Mashita K, Mitsui K (eds) Nonlinear analysis and design for shell and spatial structures. Seiken–IASS–AIJ, Tokyo
4. Tarczewski R (1997) Bar and pneumatic self-erecting space structures. In: Ciesielski R, Ciszewski B, Gronostajski J, Hawrylak H, Kmita J, Kobielak S (eds) Challenges to Civil and Mechanical Engineering in 2000 and Beyond. Wroclaw University of Technology Press, Wroclaw
5. Tarczewski R (1996) Shaping of space structures by means of shortening of cable-type bottom chord. In: Obrebski JB (ed) Lightweight Structures in Civil Engineering. MicroPublisher, Warsaw
6. Tarczewski R (2000) Variable rigidity as a tool of shaping of self-erecting structures. In: Escrig F, Brebbia CA (eds) Mobile and Rapidly Assembled Structures III. WIT Press, Southampton Boston
7. Saar OS (2000) A new type of hardening structure. In: Escrig F, Brebbia CA (eds) Mobile and Rapidly Assembled Structures III. WIT Press, Southampton Boston
8. Tarczewski R (2002) Actively adaptable structures. In: Parke GAR, Disney P (eds) Space Structures 5. Thomas Telford, London
9. Bulson PS (1967) The behaviour of some experimental inflated structures. In: Feder D (ed) Proceedings of the 1st International Colloquium on Pneumatic Structures. University of Stuttgart–IASS, Stuttgart
10. Tarczewski R (2003) Deployable inflated bridge. In: Oñate E, Kröplin B (eds) Textile Composites and Inflatable Structures. CIMNE, Barcelona