TRANSFORMABLE STRUCTURES (Review)

B.E. PATON, L.M. LOBANOV and **V.S. VOLKOV**
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

The paper deals with the main classes of transformable structures, which are shells of soft and rigid type. The main problems are outlined, which greatly reduce the range of application of such structures in modern engineering. Technical solutions, allowing optimization of functional properties of transformable shell structures, are suggested.

Keywords: *transformable structures, load-carrying shells, transformable shells*

Searching for a compromise between the need to create shell-type structures with the required parameters and possibility of their further transportation to the operation site involves addressing a wide range of engineering tasks, accompanied by upgrading of the currently available technologies and work performance in difficult-of-access places. The main problem consists in the complexity of realization in the intended structure operation site of the time- and labour-consuming process of its fabrication. On the other hand, development of engineering determines the need for shells of ever greater volume and overall dimensions, range of application of which is limited either by the absence of the respective transportation means, or their extremely high cost. The above conditions require application of special class of structures, capable of changing their geometrical dimensions in a broad range at practically unchanged mechanical properties of the material of the shell — transformable structures (TS).

The urgency of the work on TS development is due not only to appearance of new non-standard engineering tasks, requiring a search for new decisions of the respective level. A common case is that of «shell-in-shell», when upgrading or replacement of large-sized tanks in limited technological space (for instance, a compartment of an all-welded ship hull) is required.

Known is a number of TS applications, in which the transformation process is applied to solve an independent engineering task or obtain new physical properties of the object, namely excess buoyancy, rigidity, reflectivity, etc., that can be achieved in the case, when TS functional and technological characteristics meet the requirements made of its prototype.

Experience of practical application of engineering facilities of this class allows outlining the main problems, elimination of which is capable of essentially widening the sphere of TS application in engineering. Solution of these problems is reduced to ensuring multiple reproducibility of geometrical parameters, leak-proofness and stability of strength characteristics of the transformed shell.

Load-carrying shells taking the load at sufficient rigidity have the greatest applied importance. Their capability of considerable elastic displacements can be regarded as undesirable consequence of the small thickness and flatness of the shell, associated with geometrical non-linearity and loss of stability. This is exactly the property, however, which is the basis for the technology of changing the form of the shells, combining the advantages of enclosing and load-carrying structures.

In most of the cases the known TS can be conditionally regarded as bodies of shell type, which are divided into three main classes: load-carrying soft; based on transformable frame; and rigid. By the type of transformation TS are divided into structures transformed by application of excess pressure in the inner volume, and through mechanical transformation of the load-carrying frame, in particular with application of shape-memory materials. By their functional characteristics TS can be also conditionally divided into leak-proof and non leak-proof.

PWI developed a separate class of TS, which belong to hard shells and which are capable of combining the characteristics inherent to different types of transformable shells [1]. Technology of changing the form of thin-walled metal shells, to which V.M. Balitsky contributed greatly, was developed on the basis of the method of isometric bending of surfaces and combines the main advantages of the considered TS classes:

- possibility of continuous transformation of structures without application of auxiliary technological operations;
- absence of the need to maintain in the inner volume the excess pressure, used only during transformation;
- leak-proofness of the transformable shells, achieved by application of the technology of butt welding;
- absence of the need for a load-carrying frame;
- high values of transformation coefficient K_t;
- structure compactness before form change.

Developed methods of shell structure form change with preservation of topologically equivalent surface allowed creating a wide range of TS based on spatial bodies of revolution — spheres, ellipsoid, etc. Their fabrication technology is based on the methods of combinatorial geometry, and in most of the cases practical solution of the problem is realized by substitution of the surface by a family of equivalent polygons sequentially assembled by bending along the mating lines up to mutual superposition with formation of a compact pack.

The most promising in terms of effectiveness of working space utilization and convenience in manufacturing of initial billets are structures, the form of which is close to the cylindrical or conical shape [2].

Design-technological solution of TS of a cylindrical type is based on the principle of transformation of a hyperboloid fold into a shell of uniform circular cross-section. Hyperboloid fold is a complex polyhedral surface, determined by two kinds of edges, which are rectilinear generatrices of two coaxial one-sheet hyperboloids. At certain geometrical relationships such a fold is mobile in the axial direction, and can be folded compactly until its panels and edges touch each other. Owing to isometricity of the surfaces of the fold and cylinder, the stacked fold can be transformed into a cylindrical shell by pressure, created inside the volume enclosed by this shell. Here, rotation of one of the cylindrical bases relative to the other, fold form change and bending of rectilinear edges along a cylindrical surface take place. Degree of fold opening depends on the level of forming pressure, at joining of several folds along the edges a multisection hyperboloid fold can be obtained, in which each of the sections is an independent transformed element.

Figure 1 shows a transformable cylindrical shell, obtained by mating of two hyperboloid folds. Different orientation of the edges relative to the bases of cylindrical billets allows making right-hand and left-hand folds.

In unidirectional multisection systems the angle of reciprocal rotation rises in proportion to their number. The rotation, which is highly undesirable in most of the cases of potential application of cylindrical TS (for instance, docking chambers, which cannot have any deplanation or circular displacement of docking units), can be prevented at equal quantity of right and left folds.

The main disadvantages of cylindrical TS include labour-consuming technology of forming hyperboloid folds, requiring development of complex special equipment for each typesize of the end item. It was established experimentally that the optimum result in fold formation can be achieved only in a certain range of relationships $0.3 \leq H/D \leq 0.6$, where H is the height of the transformable part of the shell, D is the diameter of the shell-billet.

In most of the cases preference is given to well-established technology of TS fabrication by forming corrugated discs from thin-walled conical billets, which allows development of structures of a broad range of typesizes and parameters.

Similar to the considered case of structures of a cylindrical shape, technology of manufacturing TS of a conical type is based on the method of isometric transformation of the surface, which envisages the possibility of shell bending without material tension or compression [3]. The technology consists in changing the form of the billet (closed conical truncated shell) into a disc with multiple circular corrugations. Initial height of the cone decreases to a value, corresponding to the depth of a groove of the forming matrix.

Metal discs with circular corrugations widely used in instrument-making mostly have small dimensions and shallow corrugations. Such membranes are usually made by stamping that is unacceptable for items with deep circular corrugations at a relatively small pitch.

As the entire billet surface is deformed simultaneously, this requires a technological process with powerful pressing equipment; stamping of membranes with considerable corrugation depth cannot be per-

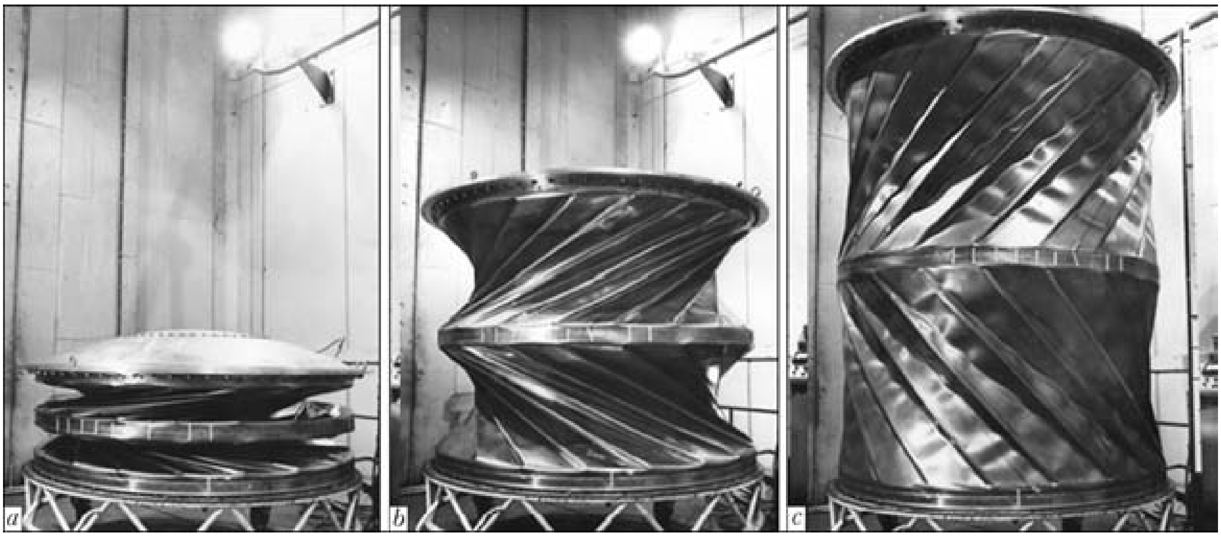

Figure 1. Transformable cylindrical two-section shell (material — 12Kh18N10T steel 1 mm thick and 2000 mm in diameter) at intermediate stages of transformation (*a*, *b*) and in the deployed condition (*c*) ($K_t = 10$)

formed in a single-step process, and a set of dies with smoothly increasing impression depth is required.

In addition, billet material undergoes considerable (up to 50 %) plastic deformations, causing work hardening and increasing its hardness. Restoration of billet ductility requires interoperational annealing, surface cleaning to remove scale, etc.

Considering the above factors, the most acceptable technology of form change of a conical billet can be regarded to be rotation extrusion by forming roller on die mold, reproducing the calculated geometry of the final corrugated disc. Technology allows forming discs of the diameter from several tens of centimeters up to several millimeters. After sealing the discs on the large and small base of initial cone, their reverse transformation into a conical shell can be performed by creating excess pressure in the inner volume. Here circular corrugations caused by local tension of material at forming and increasing the structure radial rigidity, are preserved on the shell surface.

The required number of individual corrugated discs can be joined by welding along the large and small bases into one structure, which takes the shape of a multicone shell of the required dimensions and configuration after transformation. Application of multicone shells is promising in the aerospace field, as load-carrying rods, docking modules and transfer tunnels, additional functional volumes or containers for used materials [1].

Figure 2 shows a multicone shell of a periodic profile, consisting of transformable corrugated discs (*1*), and general view of leak-proof TS after expansion (*2*), which can be accepted in development of large-sized space structures [2]. Shell diameter can be up to 4000 mm with 40 m^3 and greater volume that allows such structures to be used as accumulator tanks and storages for bulk and liquid substances [3]. Figure 3 shows a large-sized TS, used as accumulator tank in the system of self-contained water supply.

In the world practice the first TS to become accepted were load-carrying transformable soft shells, which were used in construction, in development of flying and space vehicles. Their improvement promoted appearance of new materials, combining high strength with resistance to aggressive environmental factors and small specific weight.

Figure 2. TS of a periodic profile (material — VT1-0 titanium 0.15 mm thick), consisting of 11 basic conical shells [2]: *1* — structure in the compact folded state; *2* — deployed structure

Pneumatic structures based on air-borne coverings, in which the functions of the frame are fulfilled by load-carrying pneumobottles, became accepted in building industry. The greatest functionality is characteristic for soft shells with double transformation (Figure 4): first step of volume transformation is designed for creation of basic elements of the load-carrying structure, and the second step — for creation of technological space of the required configuration on their base.

Development of polymer and composite materials on their base over the recent decades promoted emergence of a new subclass of engineering facilities, which were called air-supported structures. The load-carrying shell is fixed in the working position by maintain-

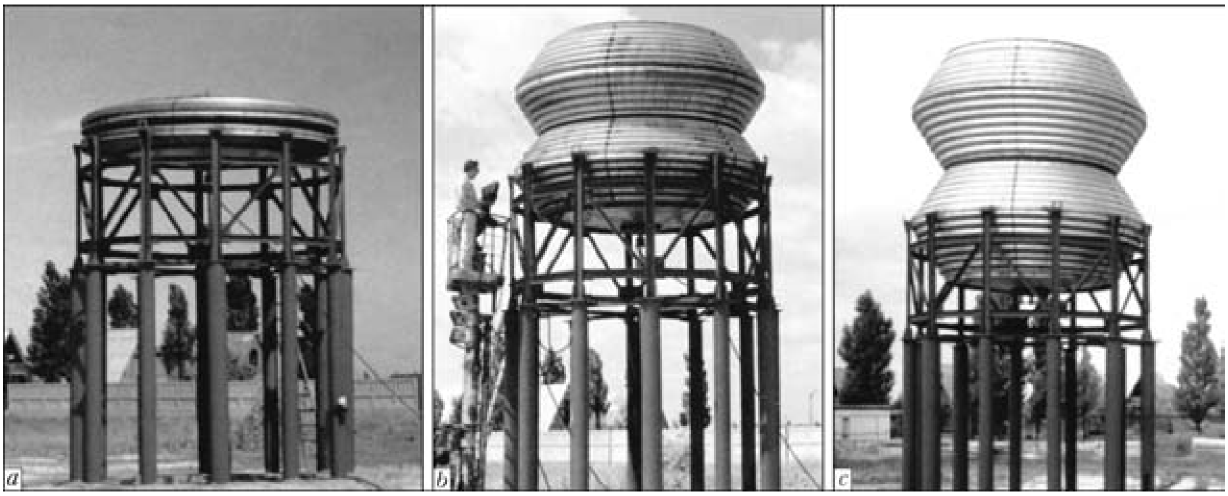

Figure 3. Large-sized TS from four conical shells (material — 08Kh18N10T steel of 2.5 mm thickness, 3800 mm diameter, 4500 mm height, 40 m^3 volume) [3]: *a* — initial; *b* — intermediate; *c* — final stage of transformation

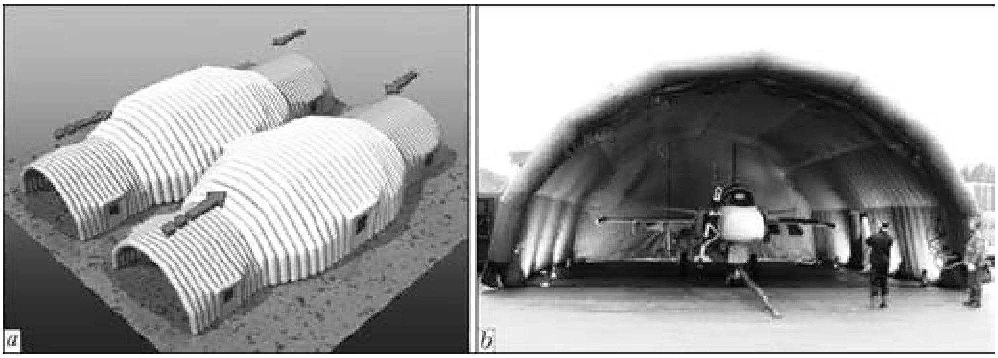

Figure 4. Air-borne structures of hangar type based on pneumobottles, designed for application as mobile living quarters and storage premises (*a*: arrows show direction of reverse transformation) and for sheltering airplanes in Swedish Airforce (*b*) [4]

Figure 5. Variants of configuration of air-supported structures of Vingida Company, Finland-Lithania [5]

ing in the service volume a slight excess pressure, not exceeding the level of normal barometric fluctuations. Soft shell from reinforced light-tight PVC fabric is hermetically fastened on the strip footing, the perimeter of which can be equal to hundreds of meters (Figure 5).

Variant of air-supported structure of radar station radome [6], made from reinforcing material of vectran type, is shown in Figure 6. Shell of 36 m diameter, 39 m height and about 8 t weight is capable of opposing wind loads, corresponding to wind velocities of more than 200 km/h without impairing the radar performance.

Application of load-carrying soft shells became one of the first successful solutions on lowering the weight of artificial Earth satellites. In particular, the USA implemented the projects of launching to near-earth orbit three research satellites and a series of commercial satellites, which represent various types of soft transformable shells. The US Naval Research Laboratory is planning the launch of a spherical research satellite, constructed on the base of a transformable frame [7]. Because of special features of the considered structures operation under the conditions of open space highly important is development of shell materials, characterized by specified properties.

Figure 7 gives the general view of a satellite with a spherical shell from synthetic polyether fibre — (mylar) — with metalized coating.

In 2009 NASA Langley Research Center (NASA LaRC) conducted a successful experiment on launching and retrieval of a lander built by ILC Dover on

Figure 6. Air-supported structure of radome on ILC Dover testing platform in the Gulf of Mexico [6]

Figure 7. PAGEOS observation satellite with 56 kg mass and 31 m diameter of the shell [8]

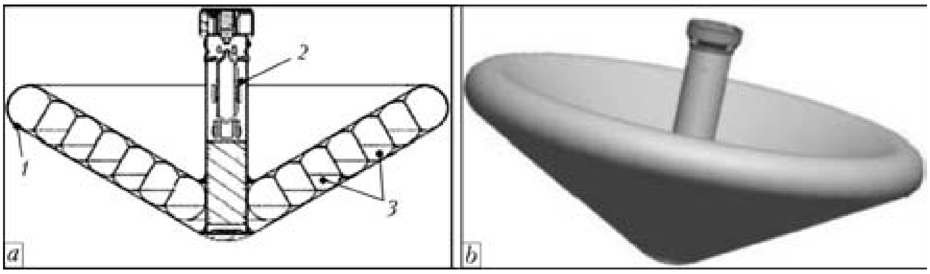

Figure 8. Schematic of a transformable lander (*a*: *1* — protective Kevlar shell; *2* — rigid central part of the structure with boosting system; *3* — torroidal load-carrying pneumbottles), and general view of the vehicle (*b*) [9]

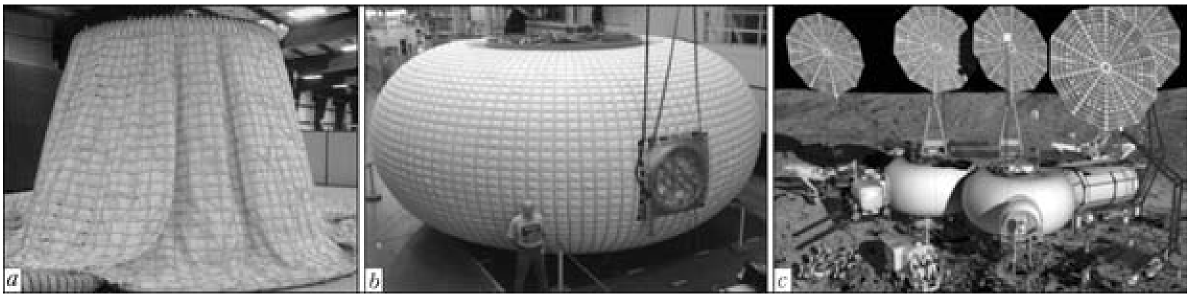

Figure 9. Torroidal Lunar Habitat: *a* — folded condition; *b* — completely deployed condition; *c* — project of NASA manned lunar outpost, constructed on the base of Torroidal Lunar Habitat [6]

Figure 10. Stages of X-Hab module transformation [6]

the base of elastic transformable shell. The vehicle was designed as a pneumatic structure with airborne covering and frame from load-carrying pneumobottles (Figure 8).

At the altitude of 211 km a kevlar shell laid into a cylindrical pack of 0.4 m diameter expanded at excess pressure up to 3 m diameter and returned to dense atmospheric layers. The experiment demonstrated the ability of structures of this class to resist pressures and temperatures, arising at passage through atmospheric layers at hypersonic velocities, while preserving the structural integrity and aerodynamic stability of the shell [9].

Joint efforts of ILC Dover and NASA on designing habitable long-term lunar outposts resulted in development of a prototype of a Toroidal Lunar Habitat, which is a transformable air-supported structure from vectran, reinforced by kevlar fibres, and rigid cylinder base for accommodation of power equipment (Figure 9).

Within NASA «Constellation» program ILC Dover developed new X-Hab Lunar Habitats, which are hybrid structures based on two metal semi-spherical shells, connected by soft cylindrical transfer tunnel of variable length with transformation coefficient, i.e. ratio of determining parameters in the initial and transformed conditions, K_t = 10–12 [6]. Figure 10 gives the stages of transformation of the structure at NASA LaRC.

In all probability, wide acceptance of load-carrying soft shells in space environment may be prevented by a rising contamination of the near — Earth space. The above structures operated in low orbits, practically free from the remnants of used space vehicles,

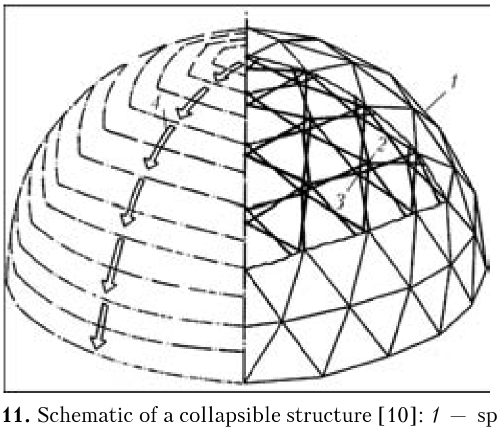

Figure 11. Schematic of a collapsible structure [10]: *1* — spherical structure; *2*, *3* — pinning points; *4* — folding direction

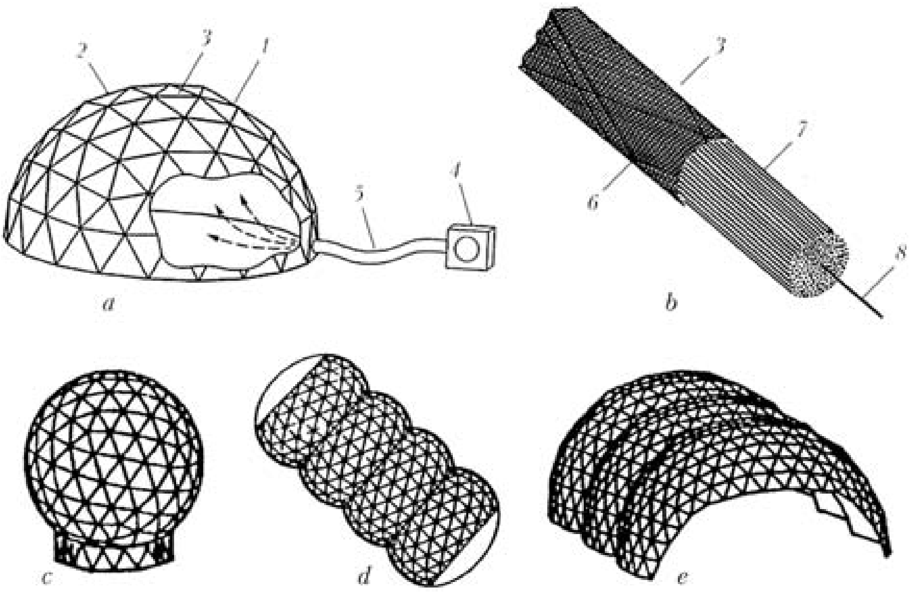

Figure 12. Schematic of an inflatable structure with variable rigidity of the shell [11]: *a* — variant of technology application for formation of sealed semi-spherical shell; *b* — element with variable rigidity; *c*–*e* — possible configurations of structures developed by this technology; *1* — transformable structure; *2* — shell outer covering from mylar or kapton; *3* — elements of variable rigidity; *4* — compressor; *5* — discharge duct; *6* — element outer covering *3*; *7* — bundle of thermoplastic fibre; *8* — heating element

and their collision with extra-terrestrial hard particles could only be of random nature.

Stationary space stations are fitted with following and orbit correction system for protection from collision with small objects; none-the-less repair and replacement of outer shell elements is included into the mandatory routine maintenance.

The obvious advantage of load-carrying soft shells consists in their capability of unlimited number of direct and reverse transformations, compactness in the folded condition and low specific weight of the structure. Coefficient of transformation K_t can reach 25–30. Their main disadvantages are absence of sufficient rigidity, need for continuous maintenance of excess pressure in the inner volume, low stability of shell material against temperature variations, ultraviolet radiation, wind load, etc.

Construction of soft shells based on load-carrying transformable frame has two main objectives: make the transformation process a single-step one, and create a frame, the configuration of which only slightly affects the structure coefficient of transformation. In a folding structure (Figure 11), pinning points *2* and *3* of load-carrying cane elements of the frame have sliding connections; forces arising in them are consecutively transferred to adjacent nodes in direction *4*. As a result, frame transformation proceeds in the direction of reduction of its horizontal section.

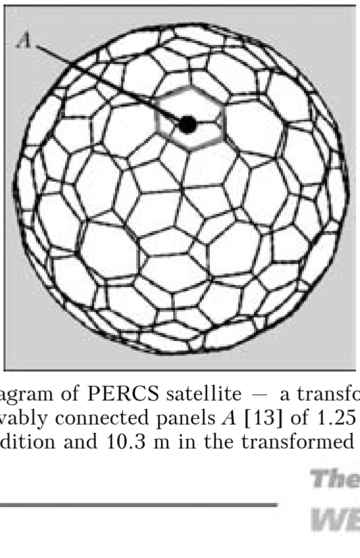

Figure 13. Diagram of PERCS satellite — a transformable sphere formed by movably connected panels *A* [13] of 1.25 m diameter in the initial condition and 10.3 m in the transformed condition

Searching for means to ensure the geometrical stability of the frame promoted emergence of structures with variable rigidity of the shell, in which application of the load-carrying base is combined with transformation using excess pressure.

Figure 12 shows the transformable shells, which are fixed in the open position using elements based on thermoplastic fibre. Element heating and their subsequent cooling lead to rigid fixation of softened fibres in the position, determined by configuration of individual frame sections.

The main disadvantage of elements with variable rigidity is the impossibility of multiple transformation of structures on their base — a characteristic property of soft shells. An alternative solution was introduction of geometrically stable load-carrying structures of complex spatial configuration, close to spherical shell.

Various variants of so-called Hoberman sphere became widely accepted, where the load-carrying frame was developed using computer simulation technologies.

Figure 13 gives the schematic of PERCS satellite, transported to orbit in the folded compact condition [12]. PERCS project can be regarded as a successful application of the technology of transformation of a shell, the leak-proofness of which is not necessary; the object belongs to the class of passive satellites and is not fitted with any hardware.

Over the recent years attempts have been made of testing shell-type transformable habitable structures out of terrestrial atmosphere. None of the announced projects, however, has been so far realized in it is full scope. In 2006–2007 Bigelow Aerospace, USA, launched to 500 km orbit the first two prototypes of habitable space stations, which are soft leak-proof multilayer shells of 150 mm thickness supported on a frame (Figure 14). After transformation by inducing excess pressure in the inner volume, module diameter increases up to 2.54 m at unchanged length [14]. At considerable specific weight of the rigid metal frame and low coefficient of transformation, the module structures lack the main advantages of flexible shells, but have the decisive advantages when being launched by rocket-carriers with a relatively small section of the transportation compartment.

Modern materials with new properties allow creating space TS, in which the transformation coefficient K_t can reach 10. However, the problem of combining these parameters with sufficient strength and leak-proofness of the shells is still unsolved. In particular, the structures of vacuum-tight shells of Genesis modules are capable of providing transformation coefficients $K_t \approx 1.6$, which under the terrestrial conditions are acceptable only at transformation of the volume of some laboratory and measuring devices, or future structures, in which parallel problems of optimization of weight-dimensional and strength characteristics are solved.

Transformation of the volume of individual elements of instruments is widely used in laboratory and measuring instrumentation, in components of piping systems, and in special stop valves, in particular tubular condensers — torroidal shells with a circular or close to circular shape of the meridian, capable of undergoing slight elastic deformations. Bellows — thin-walled tubes with circular corrugations, in most of the cases made from nonferrous metal alloys and alloyed steels, became widely accepted.

In bellows structures K_t is determined by the features of shell profile, capable of compression only within the intercorrugation spaces. Bellows are leak-proof, and can be subjected to multiple shape changes under the impact of varying pressure, but they have a special feature — loss of axial stability at inner pressure, while not having sufficient bending rigidity.

Comparative analysis of currently-available TS classes leads to the conclusion that combination of technologically acceptable strength characteristics of the shell with considerable transformation coefficients at simultaneous leak-proofness is only achievable in rigid load-carrying shells, among which conical and multicone transformable structures are the optimum variant owing to simplicity of technology. None-theless, functional qualities of this class of TS are limited by lack of well-established algorithm of multiple form change, while absence of invariance of embodiments requires development of a versatile calculation procedure of determination of basic geometrical parameters.

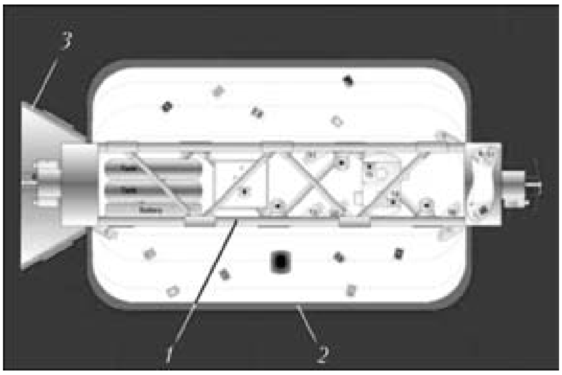

Figure 14. Genesis space module *I*/*II* [14] (1363 kg weight, 4.4 m length in the transformation condition, diameter before transformation 1.6, after transformation — 2.54 m): *1* — rigid metal frame, carrying life support systems of the module; *2* — transformable shell; *3* — docking assembly

One of the main approaches to optimization of rigid transformable shell design, allowing an essential expansion of their applications, is creation of a two-layer structure, in which the consequences of possible depressurizing can be prevented owing to duplication of the outer wall.

It was experimentally established that the process realized mainly at the expense of material bending deformation also allows performing simultaneous form change of several billets of equal geometry. Further assembly and welding of basic elements in TS are performed on circumferential load-carrying elements (frame-rings), fulfilling the functions of a jig at alignment of basic element edges, of backing during the welding process and of load-carrying element taking technological and service loads (Figure 15, *b*). Tightness of contact of two-layer shell edges is ensured by a specially developed device, which allows tying basic elements along TS axis.

After sealing the produced discs around the large and small base of initial cone, their reverse transformation into a conical shell is performed by inducing excess pressure in the inner volume. After final transformation the shell surface preserves the characteristic circumferential corrugations, caused by local tension of material in the tips of technological edges at form change and increasing the radial rigidity of the produced structure.

The purpose of the experiment with test two-layer shell consisted in determination of the influence of duplicating wall on the nature of transformation and degree of increase of excess pressure, required for structure transformation. Figure 15 gives the model of two-stage shell structure in the compact and deployed condition. The shell was fitted with a pressure gage with $0.01 \cdot 10^4$ Pa division value. At smooth increase of pressure opening of a two-layer corrugated disc proceeded in stages, starting with larger diameter corrugations and ending by smaller ones, inner shell deformation causing increase of excess pressure in the interwall space, and, consequently — opening of the outer shell.

Figure 15. Model of a two-stage transformable conical shell (material — VT1-0 titanium 0.15 mm thick): *a* — compact condition; *b* — deployed condition; *c* — axial sections of load-carrying elements (frame rings) *I* and *II*; *C*, *D* — load-carrying and auxiliary frame rings; *F* — shell bottom; *G* — transformable conical shells

After achievement of maximum pressure value for the current diameter, the corrugation deployed jumplike, pressure decreasing abruptly, because of increase of the shell inner volume; the process was repeated right up to complete transformation of TS to the calculated dimensions. Pressure required for complete transformation of the two-layer shell was equal to $P_2 = 22.1 \cdot 10^4$ Pa, and for single-layer shell with similar parameters $P_1 = (9.32–9.51) \cdot 10^4$ Pa. Thus, the duplicating wall required more than two times increase of technological pressure of transformation.

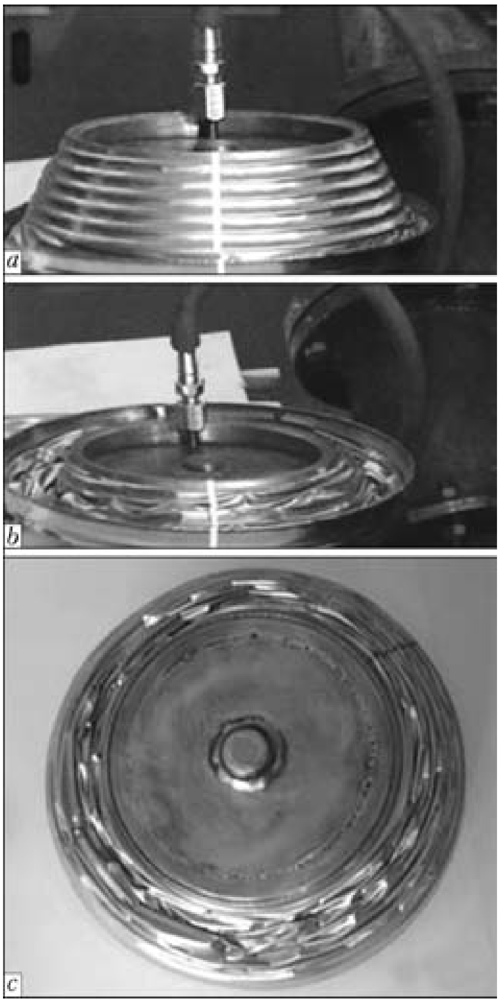

Figure 16. Reverse transformation of conical shell with sinusoidal profile of the generatrix (material — titanium VT1-0 0.15 mm thick): *a* — intermediate stage of transformation; *b* — full reverse transformation of the shell; *c* — shell appearance after complete reverse transformation

During transformation of the truncated cone into a corrugated disc and subsequent reverse transformation precise geometrical dependencies between the angle of conicity, length of cone generatrix and corrugated disc parameters are ensured, that allows simulation of the technological operations and double-shell TS components with high precision. Results obtained during the experiment allow making the conclusion about the possibility of development of extended two-stage structures, similar to the currently available multicone TS of periodical profile.

Future tasks of application of multicone TS as extendable systems and case parts of orbital space module are related to the need for their subsequent recovery, requiring optimization of the mechanism of reverse transformation with preservation of initial geometry. The capability of transformable rigid shells for multiple reproducibility of stable geometrical dimensions is in keeping with the bases of the method of regular isometric transformation. However, the real metal shell after the first repeated cycle of transformation develops wave-like deformations in the intercorrugation spaces, which are indicative of the local loss of stability (Figure 16).

During the conducted experiment a rarefaction of approximately $P = -9.32 \cdot 10^4$ Pa was induced in the model inner cavity by a vacuum pump, that corresponds to reverse value of pressure that is required for deployment of the initial corrugated disc. Within the complete transformation cycle of 33 s duration, a complete restoration of the initial shape of a two-stage shell with local deformations in the vicinity of edge tip was noted. At subsequent cycles an increase of local deformation and combining of their localization zones was noted, which leads to overall loss of structure stability.

One of the possible variants of the change of transformation technology for realization of multiple form change of the shell can be reduction of the rounding-off radius of matrix edge tips, increasing the rigidity of residual circumferential corrugations. Here, the zones of maximum elasto-plastic deformations are localized in the vicinities of the corrugation tips, and the sinusoidal profile of the conical generatrix becomes close to the shape of piecewise-broken curve, corresponding to the initial mathematical model of mirror reflection of a truncated conical surface.

Figure 17, *a* and *b*, shows the stages of reverse transformation of a model of conical TS with piecewise-broken profile of the generatrix, and configuration, corresponding to the shell, shown in Figure 16. After complete restoration of the initial shape no deformations were noted, and no zones of local loss of stability were found at three subsequent cycles. Figures 16, *c* and 17, *c* show the appearance of conical TS with sinusoidal and piecewise-broken profiles of the generatrix after complete reverse transformation. In Figure 16, *c* one can see an abrupt distortion of the shell surface in the form of multiple fractures of intercorrugation spaces, and the shell in Figure 17, *c* has completely preserved its initial geometrical dimensions.

Conducted experiments on model samples are indicative of the possibility of repeated transformation of TS with structural elements of conical type and development of two-stage TS.

Analysis of various TS classes showed that they are becoming ever wider accepted in building industry and aerospace engineering. TS developed at PWI on the base of rigid load-carrying shells are promising for application under various conditions of mounting and service, including extreme conditions.

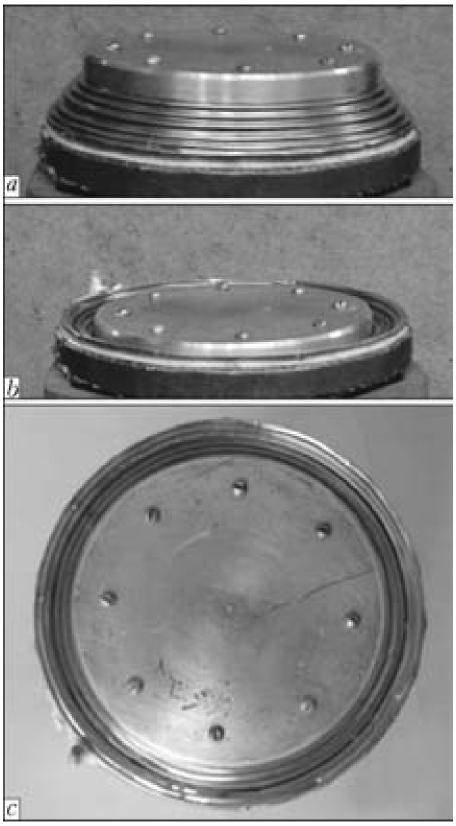

Figure 17. Reverse transformation of conical shell with piecewise-broken profile of the generatrix (material — titanium VT1-0 0.15 mm thick): *a* — intermediate stage of transformation; *b* — full reverse transformation of the shell; *c* — appearance of the shell after full reverse transformation

1. (2003) *Space: technologies, materials, structures*. Ed. by B.E. Paton. Taylor&Francis, 447–495.
2. Paton, B.E., Lapchinsky, V.F. (1997) *Welding and related technologies in space*. Cambridge Int. Sci. Publ., 88–105.
3. Paton, B.E., Lobanov, L.M., Samilov, V.N. et al. (2006) Design and features of fabrication technology of a large-sized transformable shell structure. *The Paton Welding J.*, **7**, 2–10.
4. Inflatable structures. *www.lindstrandusa.com*
5. Air-supported structures. *www.vingida.ru*
6. Air-supported installations for military purposes. *www.ilcdover.com*
7. Bernhardt, A., Siefring, C.L., Thomason, J.F. et al. (2008) The design and applications of a versatile HF radar calibration target in low-earth orbit. *Radio Sci.*, **8**, 11–21.
8. Description of PAGEOS project. *www.nssdc.gsfs.nasa.gov*
9. Hughes, S.J., Dillman, R.A., Starr, B.R. et al. (2010) Inflatable Re-entry vehicle experiment (IRVE) design overview. In: *Proc. of 18th AIAA Conf. and Seminar on Aerodynamic Decelerator Systems Technology* (Munich, Germany, May 23–26, 2010), 52–58.
10. Zeigler, Th.R. *Collapsible self-supporting structures a panels and nud therefor*. Pat. 4290244 USA. Int. Cl. E04 B1/32. Publ. 22.09.1981.
11. Sallee, B.T. *Rigidizable inflatable structure*. Pat. 5579609 USA. Int. Cl. B64699/00. Publ. 12.03.1996.
12. Self-opening satellite PERCS. *www.hoberman.com*
13. Hoberman, C. *Folding covering panels for expanding structures*. Pat. 6834465 USA. Int. Cl. E04 B1/344. Publ. 28.12.2004.
14. Module Genesis II. *www.bigelowaerospace. com*