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Tents: a paradigm of lightness and sustainability in vernacular architecture and in Frei Otto's work

KEY WORDS: Vernacular architecture, Frei Otto, tents, membrane structures, yurts, gridshells, tensile architecture, light structures, sustainability

ABSTRACT:

Purpose: The aim of this paper is to explore the relationship between vernacular architecture and Frei Otto's work, searching for shared principles and specific singularities, and testing whether lightness and sustainability can be identified as a common goal.

Design/methodology/approach: The study is focused on tents and yurts, as archetypal examples of traditional architecture, and membrane structures and gridshells, as two types of light structures developed by Frei Otto. A comparative analysis of their behavior, form, elements, types, materials and strength has been carried out.

Findings: The survey carried out shows that Frei Otto's innovative tents and gridshells were not based on form imitation of vernacular architecture, but rather on a thorough understanding of physical form-generating processes, driving specific materials to optimal form, like his experiments with soap film models to generate tensioned minimal surfaces, or his experiments with hanging chain net models to generate compressive antifunicular lattice shells.

Originality/value: This paper highlights how Frei Otto's endeavor to get the maximum with the minimum, to achieve a lot from a little, is also a key target of lightness and sustainability, and an essential feature of vernacular architecture.

1. INTRODUCTION

Among the wide variety of different building materials used in vernacular architecture, a common characteristic can be identified: the fact that in most cases, if not all, their source lies in the nearest physical environment of the built work. One could say that in vernacular architecture there is a close link between the building materials and the natural elements provided by the surrounding landscape: stone, clay, gypsum, trees, reeds, grass, animal skins, ice... Every site in the world with its climate, geology, fauna and flora has offered to all generations a source of inspiration and the basic material elements available at hand to build in a sustainable and efficient way a non-pedigree type of architecture currently qualified as vernacular.

One criterion to judge efficiency and sustainability in building is to check the amount of materials used for a specific purpose. The larger the amount, the less efficient and sustainable. This question could also be raised in vernacular architecture. How much material has been employed for a house? Does it sound reasonable in vernacular architecture to bring up the same question Buckminster Fuller once asked Norman Foster: "how much does your building weigh?" There is an area within the field of vernacular architecture in which lightness becomes a key feature of home building. Nomadic people have necessarily had to develop a type of building that would allow them to carry their homes with them in their frequent moving for hunting, fishing, collecting fruit, or tending cattle. Nomadic architecture has therefore developed a way of building homes trying to take full advantage from extremely light materials: animal skins, thin rods, strings, leather straps, woven mats, etc. It not only has managed to get maximum strength from minimum weight or amount of material, but has also worked out assembly systems allowing these homes to be easily and quickly deployed, assembled and dismantled.

Tents have been adopted by nomadic people as a light, portable and demountable home, and different types and models have been produced, depending on the geographic and climatic areas, always using linear or surface thin elements. They have become an example of lightness and sustainability in vernacular architecture. It is interesting to connect this tendency towards lightness with the history of civil and structural engineering. Since its very beginning in the eighteenth century, a strive for an economy of means and an efficient use of building materials has characterized the work of the most outstanding civil and structural engineers, always trying to obtain maximum strength with the minimum amount of material. A parallel tradition towards lightness and sustainability could be identified in the field of structural engineering, with a utopian target in the horizon: "zero weight, infinite span", as Robert Le Ricolais, one of these pioneering engineers, once put it (Le Ricolais, 1997).

Frei Otto (1925-2015), a German architect and researcher, was a milestone in that tradition towards lightness and sustainability. He defined lightweight construction (*Leichtbau*) as "a way of building with a minimum consumption of material, energetic, and economic means" (Otto, 2010). Following that principle, he invented and pioneered the use of new types of light structures, such as tensile membranes, cable nets, gridshells or branching structures. Some of these new types (tensile membranes and gridshells) could in fact be regarded as a substantial step forward in the development of traditional tents. The aim of this paper is to explore the relationship between vernacular architecture (traditional tents) and Frei Otto's work (modern tents: tensile membranes and gridshells) and to test whether the strive for lightness and sustainability can be regarded as a common ground between both.

2. TRADITIONAL TENTS

From the structural point of view, traditional tents are also known as framed tents (Burkhardt, 2000 and Drew, 1979). They are made up by two different parts, each one with its own specific role: the structural supporting frame, and the enclosure. These parts not only perform a different function, but also correspond to two distinct stages in the tent erection process. First a framework of rods, either straight or curved, and able to withstand bending, compression or tension, is set up and secured. Then an enclosure, made up of a membrane of animal skin or fabric, is stretched over the frame and fastened. The membrane enclosure or velum hangs limp or slightly tensioned from the frame, and usually adopts either a planar or a singly-curved surface geometric form. There are many different examples of framed tents, depending on the geographic and climate area, and on the materials and shapes of frames and textile coverings. Three basic groups could be identified, which will be addressed in the next three sections.

2.1 Tipi tents

These are conical tents used by the American Indians of the Plains. The frame is made up by a number of straight poles resting on the ground at one end, and tied in the tent's apex near the other end. The ground floor plan is oval, and the entrance is set at one end of the longer radius. First a foundation frame of three or four poles is erected (Figure 1), and then the rest of the poles are placed on specific points on the ground and laid on the foundation frame's apex. The tipi is slightly tilted towards the direction of the prevailing winds, for better protection. This backward tilt positions the tent's apex away from the centre of the floor plan, which is occupied by the fire and, in its vertical projection, by the smoke hole. That allows also higher clearance at the back of the tent. An anchor rope is lashed around the frame's apex, pulled down, and fastened to a peg on the floor (Figure 2).

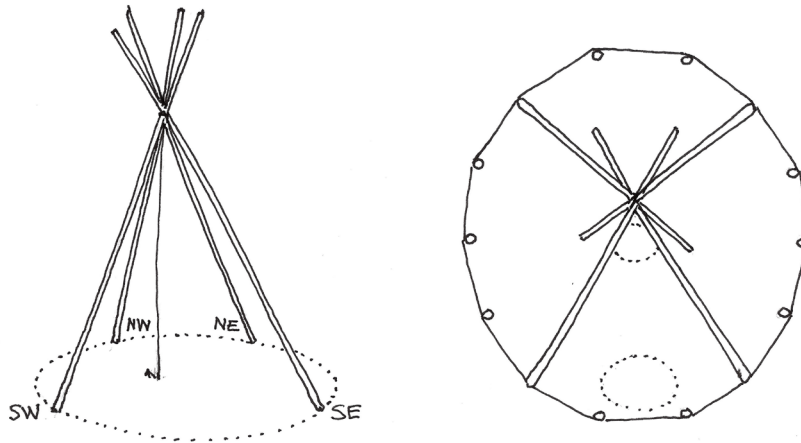


Figure 1. Four-pole foundation frame of a tipi tent. ©Author's drawings

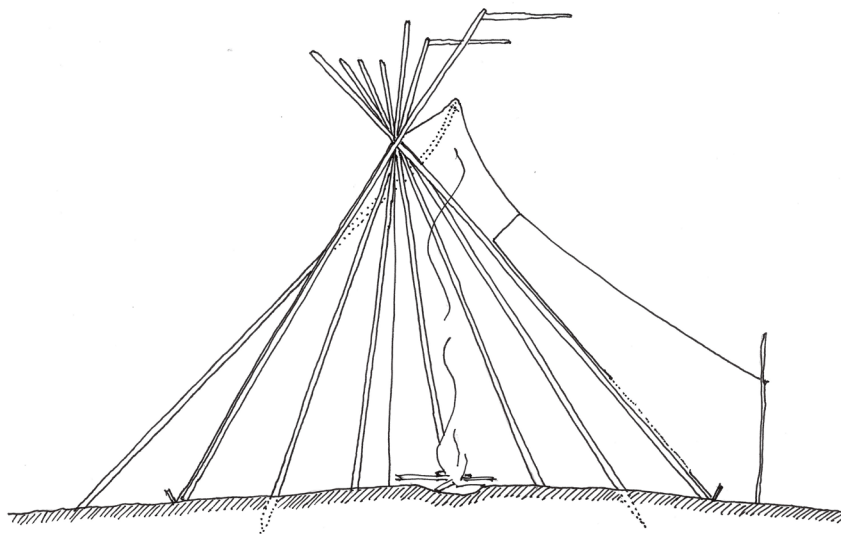


Figure 2. Cross section of a tipi tent. ©Author's drawing

The tent's cover, a semi-circular piece of animal skin or canvas, is lifted and stretched around the conical frame (Figure 3). The straight sides of the cover meet at the front, and are laced by wooden or bone pins, leaving a round doorway at the bottom and a smoke hole on top. The semi-circular edge of the cover is fixed to the ground with stakes. Two flaps around the smoke hole are extended and directed, according to the wind direction, with a pair of long outer poles attached to their upper angle. This makes up an efficient ventilation system, which prevents smoke concentration inside the tent (Figure 4).

The tipi tent can easily and quickly be pitched and taken down, and all its parts are light linear or surface elements, which can be carried without difficulty by dogs or horses. The poles are bundled and attached to both sides of the animal on their lighter end, letting the other heavier end rest on the ground, to be dragged along. The cover is folded following a standard pattern and fastened onto a packsaddle.

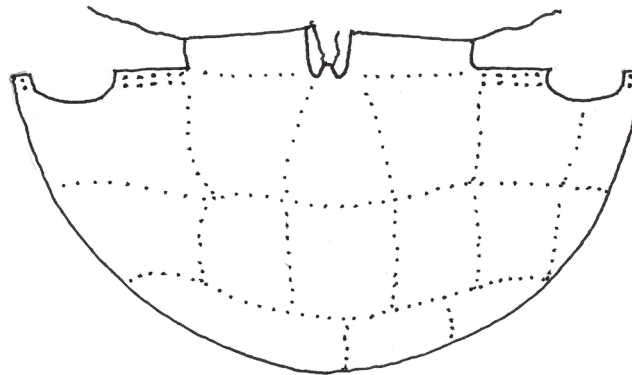


Figure 3. Animal skin cover of a tipi tent. ©Author's drawing

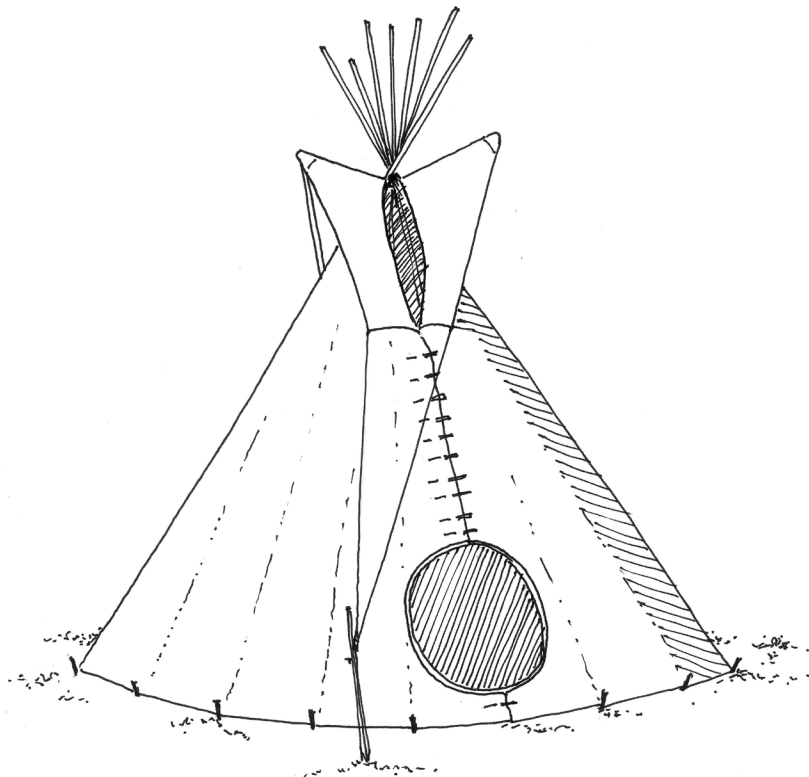


Figure 4. Outside view of a tipi tent. ©Author's drawing

2.2 Black Bedouin tents

The black tent embraces a wide territory from the Atlantic coast in Mauritania, across North Africa and Arabia, till Afghanistan, with an isolated area in Tibet. It is therefore a tent type which has adapted to different sorts of environments: mountains with some

rainfall, and deserts with a burning sun and occasional sandstorms. The dwellers of the black tents are nomads using camels as their main means of transport and seeking pastures for their flocks. Goats and sheep provide the material for one of its main elements: the characteristic black velum. These black-tent people weave the cloth for their roofs with yarn spun with goat hair and sheep wool fibre. Goat hair meets best the requirements of length and tensile strength. The width of the woven cloth is the basic module of the roof velum. Several strips of woven cloth sewn lengthwise side by side make up the roof rectangle (Figure 6).

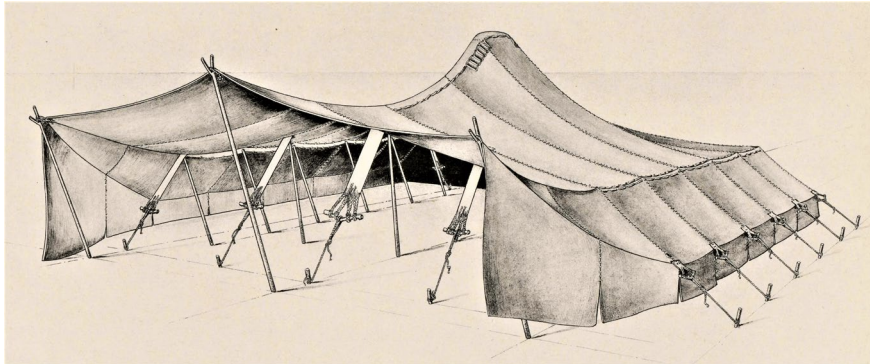


Figure 5. Maghrebi Central Algerian tent. © Ernst Rackow & heirs © UB der HU zu Berlin, Historische Sammlungen: LA 1255

The frame supporting the velum is made up by a few isolated and compressed poles, therefore using a minimum amount of wood in relation to the tipi and yurt frames. The velum is reinforced by tension straps sewn across the strips of cloth and their seams. These straps are fastened at their ends to guy ropes or stays, which are anchored into the ground by stakes (Figure 5). The velum is therefore supported by a structural system comprising the tension straps, where the tension of the pulling stays is concentrated, the underpinning poles, the stays and the stakes. Although the velum is prestressed, tension is not high enough to prevent some flapping when wind blows, and its synclastic surface shapes do not ensure that every point of the velum is fixed by two opposing forces. Nevertheless, the black tent is the type of tent closest to modern twentieth century tents.

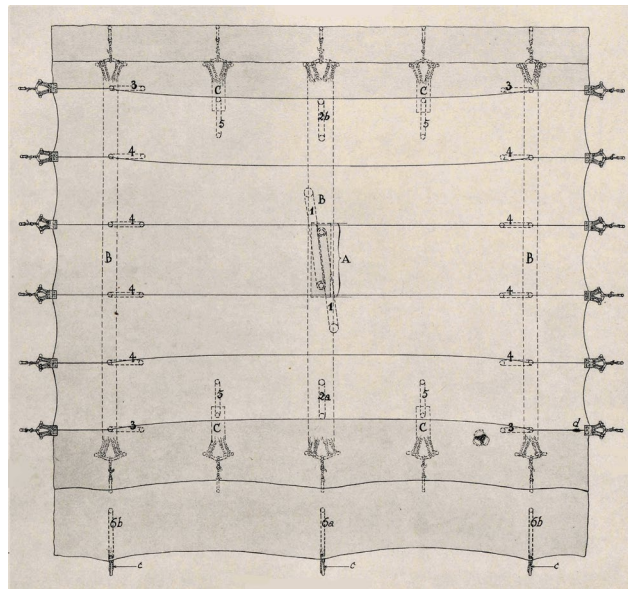


Figure 6. Maghrebi tent. Velum extended on a flat ground. View from above. © Ernst Rackow & heirs © UB der HU zu Berlin, Historische Sammlungen: LA 1255

The Central Algerian tent is a good example of black Bedouin tent. Its velum comprises the actual roof, which is a central rectangle five strips of cloth wide, and two hanging panels two strips of cloth wide each, which are either sewn or fastened to the front and back edges of the roof rectangle. The velum descends close to the ground, and this makes unnecessary any additional walls on either side. The roof rectangle is reinforced by three straps of tightly woven cloth sewn on its underside, running along the full depth of the roof, and perpendicular to its five strips of cloth and their corresponding seams (Figure 6). There is a central wider strap and two narrower side straps. Depending on the size of the tent, other auxiliary short straps may be inserted in the roof front and back edges, between the central and side main straps. Three rows of poles support these three main straps. The poles supporting the side straps are located under each seam of the five strips of cloth which make up the roof rectangle. There is also a pole supporting each auxiliary short strap. In the middle of the tent there are two higher main poles, usually crossed, supporting a slightly curved ridge wooden piece on which the central strap rests (Figures 7 and 8). They give the Maghreb tent its characteristic humped form (Rackow, 1938 and Drew, 1979).

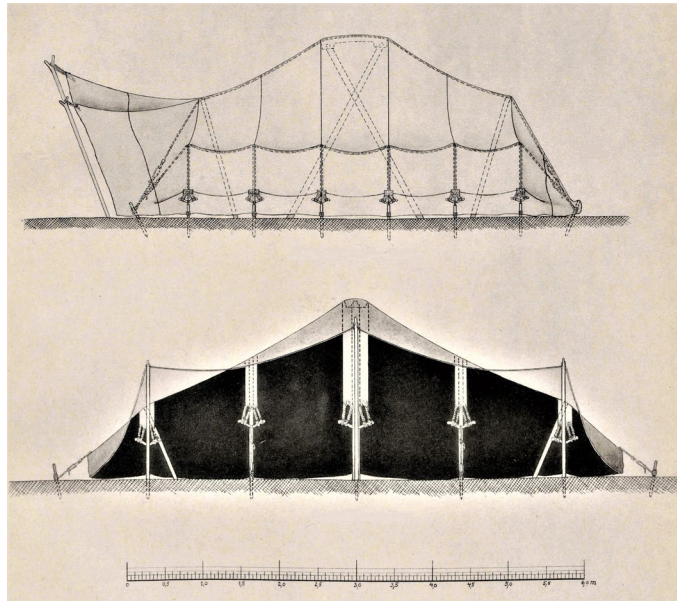


Figure 7. Maghrebi Central Algerian tent. Side and front elevations. © Ernst Rackow & heirs © UB der HU zu Berlin, Historische Sammlungen: LA 1255

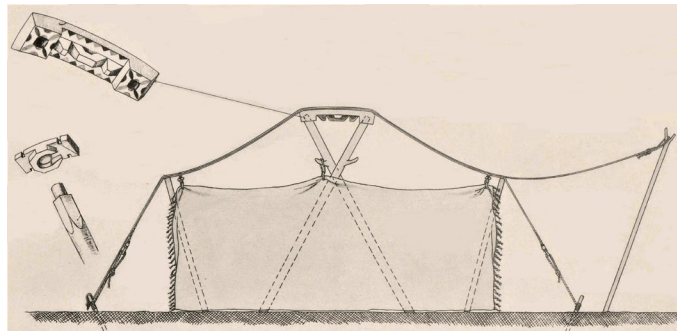


Figure 8. Maghrebi Central Algerian tent. Cross section with separating curtain. © Ernst Rackow & heirs © UB der HU zu Berlin, Historische Sammlungen: LA 1255

2.3 Yurts and khibitkas

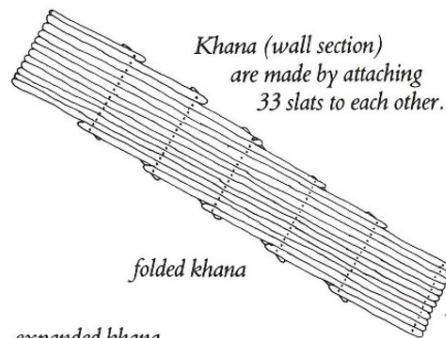
The yurt (Turkic), ger (Mongol) or khibitka (Russian) is a portable tent used by the nomads of Central Asia, whose form is very close to the dome, enclosing maximum space with minimum surface. It is made up by a cylindrical base and a conical or doubly curved synclastic roof, an aerodynamic shape most appropriate to confront the flow of fierce winds, and to ensure optimal energetic performance, reducing heat loss and heat gain. The yurt basically consists of a limp felt cover stretched over a self-supporting wooden frame, needing no poles inside, and no stays or stakes outside (Figure 9). All its elements are standardized and most suitable for multiple transportation, erection and dismantling, providing at the same time lightness, flexibility and strength. A yurt can be erected or dismantled in less than an hour (Faegre, 1979).



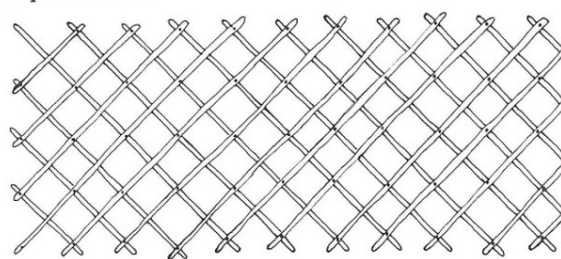
Figure 9. Yurt. Inner frame and outer felt covering tightened with ropes. ©Author's drawing

The frame includes a cylindrical wall made up by lashing several sections of deployable lattices (khanas), a ring (crown) on top of the roof, and a series of radial roof poles supporting the roof ring and resting on the wall lattice. The ends of the lattice wall are lashed to both sides of the door frame. The yurt frame does not use thick poles, as it must be light and portable, and also because the yurt territory is wood-scarce. Instead, it is made of slender willow poles, split for the khana, and whole for the roof poles (Faegre, 1979). The lattice wall sections or khanas consist of a grid of crossing slats with a hinged joint at each crossing to allow the folding and expanding movement. It forms a square mesh of about 30.5 cm when extended. The upper ends of the roof poles are inserted in the roof ring edge, whereas the lower ends are tied to the V-shaped crisscrosses at the top of the wall diagonal lattice. A tension band must be tied all around the top of the wall, in order to absorb the outward thrust of the roof poles (Figure 10).

The Walls

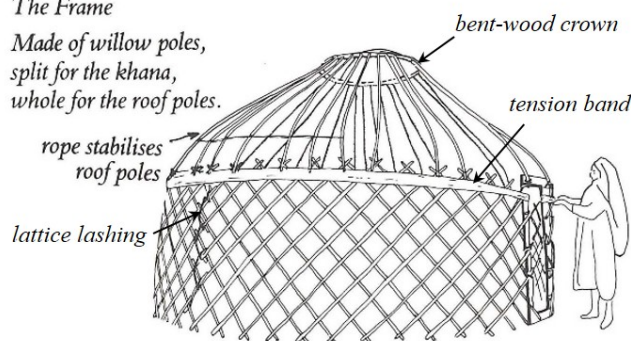


expanded khana



The Frame

Made of willow poles, split for the khana, whole for the roof poles.



The roof ring or crown is made of bent wood, and is one of the key features of the yurt. It overcomes several deficiencies of the conical tent. It makes a foundation structure unnecessary, and liberates the smoke hole from the bundle of poles which accumulate at the apex of the conical tent, as the upper ends of the yurt roof poles are spread around the roof ring or crown. Moreover, it allows light and air into the inner space, an easy escape of smoke from the hearth, and also acts as a clock (Drew, 1979).

The structural efficiency of the yurt frame is remarkable, as it develops great strength with extremely light, thin and flexible rods. By extending and curving slightly the slats of the foldable square-mesh lattice wall sections, the wall becomes a simply curved cylindrical surface, with a great capacity to resist compression forces.

3. MODERN TENTS

After reviewing three basic types of traditional tents, their materials, technology, building elements and behavior, the work of Frei Otto will now be surveyed as a major contribution in the development of this vernacular architectural typology, and in the pursuit of lightness in structural engineering, with new modern materials, designs and technologies. Till Frei Otto, traditional tents were ephemeral and portable constructions used by nomads to enclose small spaces with short spans. Prestressed textile membranes and compressive antifunicular lattice shells or gridshells appeared with Frei Otto in the mid-twentieth century, to cover larger spans and to give rise to more durable constructions.

3.1 Tensile prestressed tents

In traditional or framed tents a self-supporting frame is erected and then a covering of animal skin or fabric is draped over it. There are two subsequent actions. In modern prestressed tents there is a textile membrane, a key structural element with a great tensile strength, which is set up while the structure is being assembled. Structure and covering are unified and belong to one single assembly process. Space, roof and structure coincide in the same form, the most effective one to achieve strength and stiffness with membranes, and one of their most characteristic features: anticlastic doubly curved surfaces, also known as saddles.

Textile membranes are extremely thin and light structural elements. Self-weight is not an important problem in relation to stiffness or form stability. If they hang limp or if they are pulled all around the edges of a planar surface, flapping will be inevitable when wind blows. The problem is therefore how to ensure a permanent position for all points of the membrane. Frei Otto experimented with soap films developing minimum surfaces with equal stresses in all its points, and found that doubly curved anticlastic surfaces or saddles were the most appropriate forms to stiffen membranes, as due to the stress distribution every point in the membrane gets its position fixed by the interaction of two opposing forces (Figure 11).

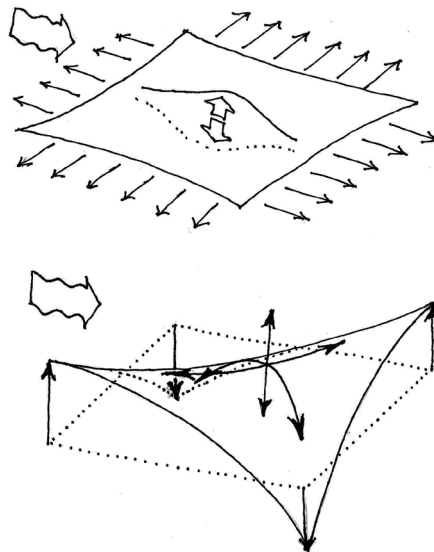


Figure 11. Membrane stiffening by an anticlastic prestressed surface. ©Author's drawing

Tensile prestressed membranes have been a milestone in the strive towards lighter structures bridging larger spans, as they have overcome the problem of buckling of thin compressed shells, which was an important limit in that strive. Different types of prestressed tents were developed by Frei Otto with the collaboration of the German tent manufacturing company L. Stromeyer & Co. Most of these prototypes were built for the German Federal Garden Exhibitions of Kassel (1955), Cologne (1957) and Hamburg (1963). An overview of some basic types of prestressed tents developed by Frei Otto will be carried out in the next sections.

3.1.1 Anticlastic curved four-point tent: This is the most elementary type derived directly from the basic anticlastic doubly curved minimal surface, developed between two diagonally opposed high and low points.



Figure 12. Music Pavilion. Federal Garden Show. Kassel, 1955. ©Atelier Frei Otto + Partner

These saddle forms were also obtained by Frei Otto with his experiments with soap films, exploring how they develop minimal surfaces. Models were built changing the position of high and low points, using flexible and rigid edges, with straight and curved or regular and irregular linear forms (Figure 13).

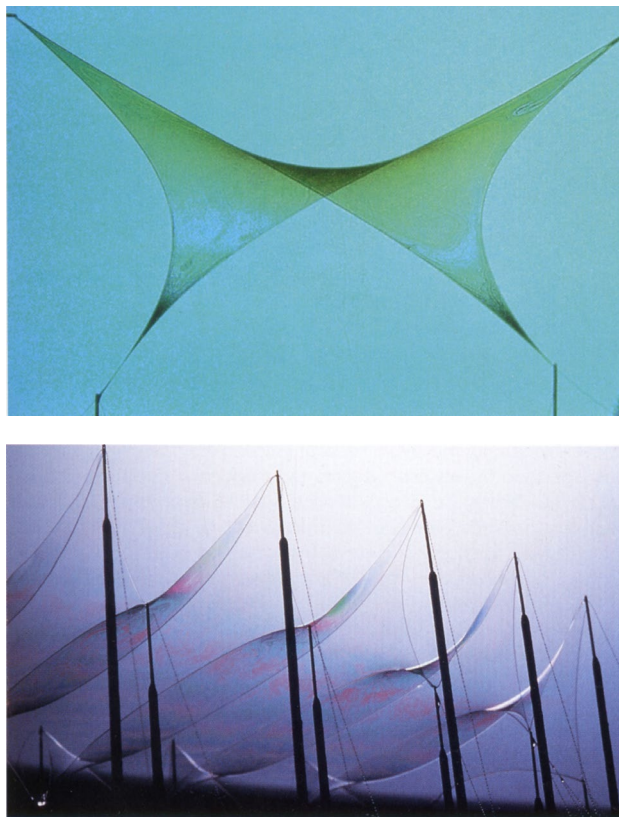


Figure 13. Soap film saddle models. ©Atelier Frei Otto + Partner

3.1.2 Wave tent with ridges and valleys: The main formal feature of this type of prestressed tent is the alternating sequence of high and low points along the membrane edges, generating a pattern of alternating ridges and valleys. The surfaces between them are anticlastic and very appropriate for water draining. This sequence of ridges and valleys creates an undulating longitudinal cross section, and depending on their layout the waves can be parallel or radial (Figure 14).

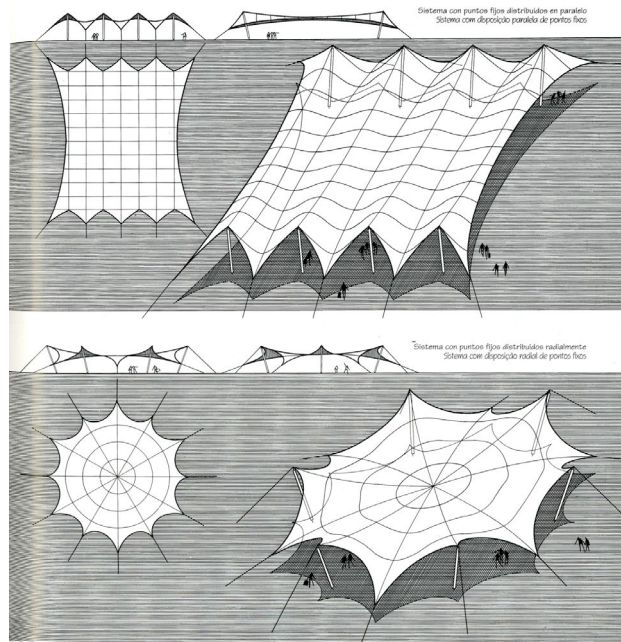


Figure 14. Parallel and star wave tents. ©Heino Engel



Figure 15. Parallel wave tent. International Garden Show. Hamburg, 1963. ©Atelier Frei Otto + Partner



Figure 16. Star wave tent. Dance Pavilion. Federal Garden Show. Cologne, 1957. ©Atelier Frei Otto + Partner

3.1.3 Arch-supported tent: Membranes of this type of tent are prestressed by the anticlastic minimal surface developing between an inner linear rigid arch springing from the tent perimeter, and the tent edges, which can be flexible or rigid linear elements.

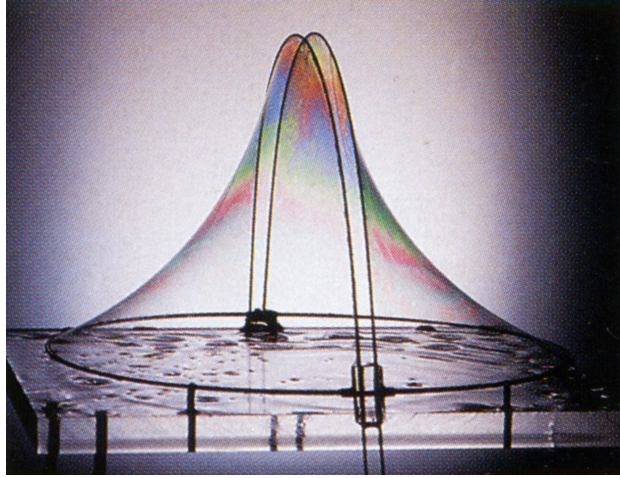


Figure 17. Arch-supported soap film minimal surface model. ©Atelier Frei Otto + Partner



Figure 18. Arch-supported entrance canopy. Federal Garden Show. Cologne, 1957. ©Atelier Frei Otto + Partner

3.1.4 Pointed, humped, and high-and-low-point tent: Prestressed anticlastic surfaces are generated in this type of tent by inserting internal high points, or low points, or a combination of both. A key problem here is the stress concentration at those internal points of the membrane. Frei Otto designed different intermediate elements between these internal points and the membrane to gradually reduce and distribute evenly these high stresses within the membrane.



Figure 19. Humped tent. Federal Garden Show. Cologne, 1957. ©Atelier Frei Otto + Partner



Figure 20. Mast tip split in a bundle of rods. Federal Garden Show. Cologne, 1957. ©Atelier Frei Otto + Partner

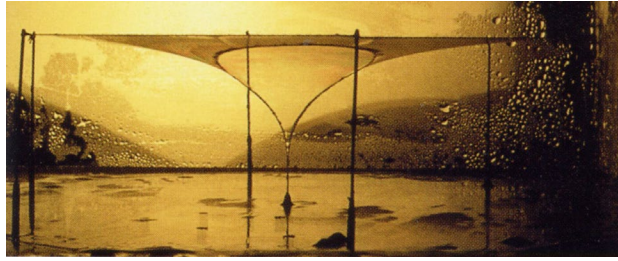


Figure 21. Soap film minimal surface with a low point made up by a loop pulled downwards. ©Atelier Frei Otto + Partner



Figure 22. High point with a cable loop in a cable net. German Pavilion. Montreal Expo 1967. ©Atelier Frei Otto + Partner

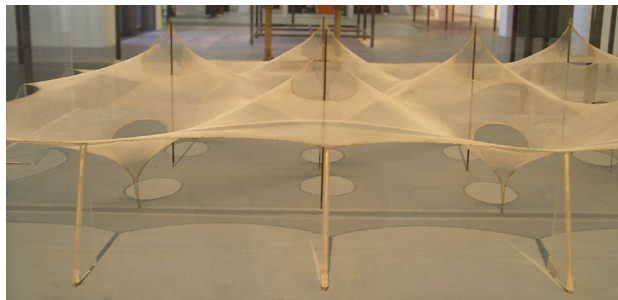


Figure 23. High-and-low-point tent model. ©Author's photograph

3.2 Compressive antifunicular lattice shells

After having experienced the possibilities offered by tensile membranes, Frei Otto explored the field of compressed vaults, experimenting with hanging funicular models. He developed hanging chain net models to find the most suitable form for a compressed vault made of a lattice of thin wooden slats. It was in fact a new type of light thin shell, which he named *Gitterschale*, usually translated as “gridshell” in English. Its form-finding process was based on Hooke’s principle of inversion: “As hangs the flexible line, so but inverted will stand the rigid arch.” If a catenary is the most suitable form for a hanging chain to work in tension only, the inverted catenary will be the optimal form for an arch to work in compression only, assuming that gravity is the sole external action. This is a key principle of gridshells: the use of antifunicular forms, obtained from a hanging chain net model (Figure 24 and 25).

The building process of gridshells is another important feature and a key principle of this new type of structures. It starts with a flat orthogonal square-mesh thin slat grid lying on the floor, with loose hinges at every slat crossing. Some points in the central area are hoisted up, and the flat grid is gradually deformed into the antifunicular form obtained by the hanging chain net model. The initial flat planar surface becomes a doubly curved synclastic surface (Figure 26). The thin slats bend slightly, and rotate around each hinge, transforming the initial right angles into sharp ones, and the initial square meshes into rhombic ones. Once the desired antifunicular form is reached, the hinges are tightened, the angles become fixed, and the gridshell becomes stiff (Figure 27).

Compared with thin reinforced concrete or ceramic shells, gridshells are a step forward towards lightness and sustainability. Their main material is thin wooden slats or metal rods, much lighter than reinforced concrete or ceramics. The doubly curved shell surface is generated by linear elements, instead of continuous and opaque surface elements. The curved lattice of gridshells leaves large voids between the slats or rods, lightening the shell even more, and allowing natural light through a great percentage of the gridshell surface (Figure 30).

Considering the boundary conditions of the first experimental gridshells developed by Frei Otto in 1962, two basic types of gridshells can be identified: open mesh arch boundary gridshells and closed flat boundary gridshells (Engel, 1997).

3.2.1 Open mesh arch boundary gridshells: The edges of the gridshell coincide with the peripheral grid lines. All the meshes of the grid are closed and complete. The outline of the flat grid is a square or a rectangle. Supports are punctual.

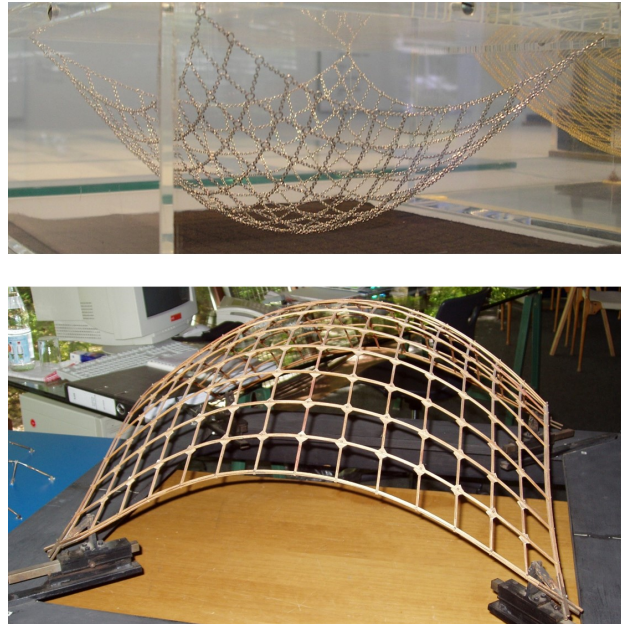


Figure 24. Hanging chain net with open mesh arch boundary, and inverted funicular model. ©Author's photographs

3.2.2 Closed flat boundary gridshells: The edges of the gridshell do not coincide with any grid line. The boundary edges can have any form, and the ends of the slats are fastened to them. The peripheral meshes of the grid are cut, open and incomplete. Supports are linear.



Figure 25. Hanging chain net with close flat boundary, and inverted funicular model of Frei Otto's *Deutsche Bauausstellung* gridshell. Essen, 1962. ©Author's photographs

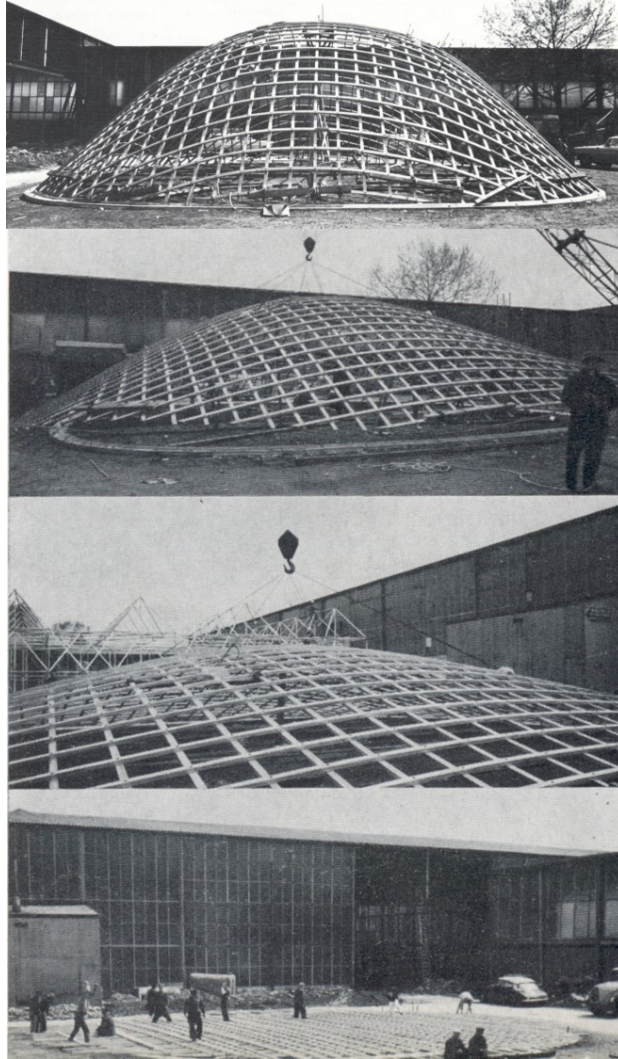


Figure 26. Building process of Frei Otto's *Deutsche Bauausstellung* gridshell. Essen, 1962. ©Atelier Frei Otto + Partner

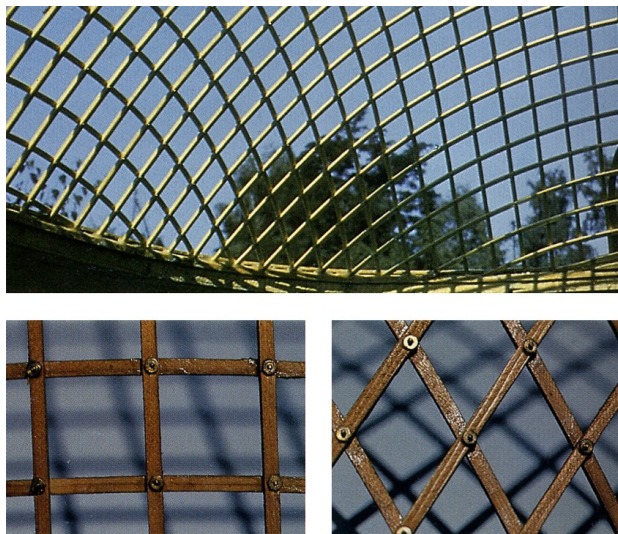


Figure 27. Doubly curved synclastic shape develops as grid is hoisted up, slats rotate at intersections, and initial mesh squares deform into rhombi. ©Atelier Frei Otto + Partner

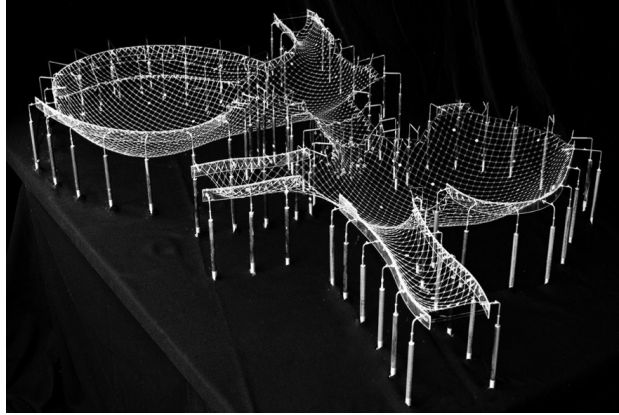


Figure 28. Frei Otto's hanging chain net funicular model of Mannheim Multihalle gridshell. ©Atelier Frei Otto + Partner

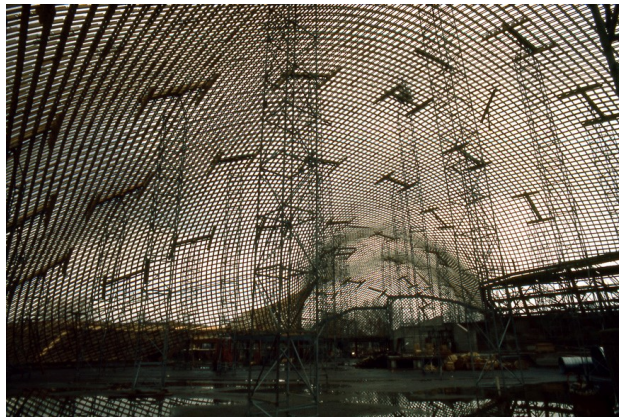
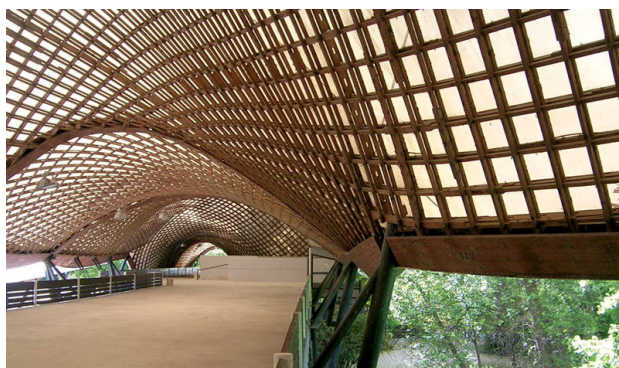


Figure 29. Building process of Mannheim Multihalle gridshell. ©Atelier Frei Otto + Partner



4. CONCLUSION

As a final discussion, some specific points and concluding remarks have been highlighted to yield a detailed and concise summary concerning the structural behavior and geometric forms of vernacular architecture (traditional tents) and Frei Otto's work (modern tents: tensile membranes and gridshells).

Concerning tensile tents – both traditional and modern – the basic structural elements are two-dimensional or surface tensioned textile membranes, whereas concerning yurts and gridshells the structural frames are made up by one-dimensional or linear elements – compressed and slightly bent slats – deployed into a two-dimensional or surface pierced shell.

If traditional or framed tents are confronted with modern prestressed tents developed by Frei Otto, the following specific points can be remarked:

- In traditional or framed tents, the fabric hangs from a preset frame of rods and/or straps, with scant prestressing and an uneven distribution of tension stresses. In modern prestressed tents, a textile membrane is evenly tensioned in all directions.
- In traditional or framed tents, wind may cause flapping, as fabric hangs limp, whereas in modern prestressed tents shape stability against wind flapping is assured by using anticlastic doubly curved surface geometries, also known as saddles.
- In traditional or framed tents, shapes developed usually involve flat, singly curved or doubly curved synclastic surfaces, as found in cones, hemispheres, cylinders, pyramids or cubes (Drew, 1979), whereas in modern prestressed tents anticlastic doubly curved surfaces are the most usual shapes.
- In traditional or framed tents, spans bridged are short, and spaces enclosed small, whereas in modern prestressed tents, spans covered are longer, and spaces enclosed larger.

Confronting yurts and gridshells, the following aspects can be pointed out:

- In yurts, the structural frame includes a cylindrical wall, made up by a foldable diagonal lattice of slats, and a domical roof, made up by a set of radiating flexible poles converging in a wooden ring on the top. In gridshells, the structural frame is made up solely by a square-mesh timber slat grid, which is spread flat on the ground, and hoisted up to adopt the inverted form of a hanging chain net model.
- In yurts forms are not antifunicular or catenary, whereas in gridshells they are antifunicular or catenary.
- In yurts the supporting wall is a lattice which develops into a singly curved cylindrical surface, whereas in gridshells the slat grid produces a doubly curved surface.

The comparative analysis developed in this paper between vernacular architecture and Frei Otto's work makes evident that his innovative tents and gridshells were not based on form imitation of vernacular architecture, but rather on a thorough observation and analysis of physical form-generating processes, driving specific materials to optimal form, like his experiments with soap film models to generate tensioned minimal surfaces, or his experiments with hanging chain net models to generate compressive antifunicular lattice shells. A common strive towards lightness and sustainability can be identified in vernacular architecture (traditional tents) and in Frei Otto's work (modern tents), which does not depend on mutual form imitation, but on an effort to take full advantage of either local and traditional or of everyday and modern materials to obtain best performance with minimum amount.

REFERENCES

- Andrews, P. A. (1997), *Nomad Tent Types in the Middle East, Part I: Framed Tents*, Dr Ludwig Reichert, Wiesbaden.
- Burkhardt, B. (2000), "Geschichte des Zeltbaus. History of Tent Construction", *Detail*, Vol. 40 No. 6, pp. 960-964.
- Drew, P. (1979), *Tensile architecture*, Crosby Lockwood Staples, London.
- Engel, H. (1997), *Structure Systems*, Gerd Hatje, Ostfildern-Ruit.
- Faegre, T. (1979), *Tents, architecture of the nomads*, Anchor Press, New York.
- Faegre, T. (1982), "The Kazak Yurt", *Mimar*, No. 4, pp. 50-55.
- Feilberg, C. G. (1944), *La tente noire, contribution ethnographique à l'histoire culturelle des nomades*, Nordisk Vorlag, Copenague.
- Hennicke, J. and Hasegawa, T. (Eds) (1974), *Gitterschalen / Grid shells*. IL 10, Institut für leichte Flächentragwerke, Stuttgart.
- Le Ricolais, R. (1997), *Visiones y paradojas. Visions and paradox*, Fundación Cultural COAM, Madrid.
- Meissner, I. and Möller, E. (2015), *Frei Otto. Forschen, bauen, inspirieren. A life of research, construction and inspiration*, Detail, Munich.

Nerdinger, W., Meissner, I., Möller, E. and Grdanjski, M. (Eds) (2005), *Frei Otto: complete works: lightweight construction natural design*, Birkhäuser, Basel.

Otto, F. and Songel, J. M. (2010), *A conversation with Frei Otto*, Princeton Architectural Press, New York.

Otto, F., Burkhardt, B. and Bächer, M. (Eds) (1978), *Multihalle Mannheim*. IL 13, Institut für leichte Flächentragwerke, Stuttgart.

Rackow, E. and Caskel, W. (1938), "Das Beduinenzelt", *Baessler-Archiv*, Vol. 21 No. 4, pp. 151-184.

Roland, C. (1972), *Frei Otto: structures*, Longman, London.

Wilhelm, K. (1985), *Portrait Frei Otto*, Quadriga-Verlag Severin, Berlin.