„Foldable structures – explanation and drawings for the patent specification“ By Dipl. Ing. Friedrich B. Grimm, Stuttgart in summer 1987

I Foreword

This paper describes technical applications resulting from the advantageous properties of foldable node-rod systems and illustrates them with drawings. Based on numerous model studies in which the spatial foldability of modular surface structures was proven to be a generally valid phenomenon for even numbered, regular polygons and their arrangement in a grid system, this study is less concerned with the theory of these structures than with an investigation of their practical applicability in construction engineering. A fundamental description of the geometric conditions for the spatial foldability of modularly structured surfaces was only provided to the extent necessary for explaining the practical applications. Foldable node-rod systems are initially unstable structures. They are kinematic and describe different states, the extremes of which can be seen in complete unfolding and complete folding. In the unfolded state, all nodes lie on one plane. During spatial folding, the nodes divide into upper and lower nodes, defining two planes. In the folded state, all rods of the structure lie parallel to each other and the alignment into lower and upper nodes is complete. Various measures can be taken to convert unstable structures into stable ones. On the one hand, the individual joints of the fully unfolded structures can be stiffened by appropriate measures, and on the other hand, the “upper and “lower” nodes of a partially unfolded structure can be connected with plates or plate-shaped elements or even with a fully unfolded structure, thereby creating spatial supporting structures. Suitable details for these tasks are presented in several chapters. In the last chapter, “Foldable Structures in Nature,” I have taken the liberty of transferring the observations on spatially foldable node-bar systems to the structural models of the natural sciences.

II The spatial foldability of even-numbered polygons

All even-numbered, equilateral polygons whose corners have been replaced by nodal bodies and whose sides have been replaced by rods connected to the nodal bodies by pivot joints form a spatially foldable node-rod system. During the folding process, all rods of the system are subject to a constrained mechanism that transforms the horizontally unfolded node-rod system into a vertically aligned bundle, so that when fully folded, the rods are perpendicular and parallel to each other. The pivot pins of the rotary joints are each perpendicular to the longitudinal center axis of the rod. The rotary joint is formed by a tongue and a fork, which are connected to each other by a pivot pin. The fork can belong either to the node body or to the rod. If the longitudinal center axis of the rod is to remain free for reasons of system integrability, both the node body and the rod are equipped with a fork. Two bolts, pins, blind rivets, or shear sleeves are then required for each joint.

III The spatial foldability of flat link networks

Not only individual, even-numbered polygons with equal side lengths are spatially foldable, but also their modular arrangement in a grid system. When unfolded, the node-rod system forms a network whose meshes are formed by pressure rods connected to the nodes by pivot joints. For this reason, I will refer to the unfolded structure as a flat link network in the following. Here, too, the prerequisite for the foldability of the structure is that the polygons that make up the network are even-numbered. The spatial folding of the structure is also a forced mechanism in which all rods are involved simultaneously, transforming the horizontally unfolded link network into a vertically aligned bundle of rods. During the folding process, “high and low points” occur in the link network. If one imagines that the network of members is spread out on an equatorial plane, then one half of the nodal bodies involved in the folding would migrate to a lower, southern pole, and the other half to an upper, northern pole. The height of the fully folded structure corresponds to the length of a single rod. When unfolded, the height of the system is equal to the rod diameter. The geometric order of the node-rod system can be chosen so that the rods touch each other when folded, so that they are perpendicular and parallel to each other. In this case, the densest possible packing of a foldable link network is achieved. The geometry of the link network is always preserved, regardless of the state of unfolding of the structure. An unfolded hexagon also obeys the geometric order when fully folded, with the connecting lines of the longitudinal axes of the rods also forming a network of hexagons.

IV Instability and stability in foldable node-rod systems

Flat, spatially foldable node-rod systems are either individual, even-numbered and mostly equilateral polygons or their modular sequences. The sides of the polygons are formed by rods, while the corners or intersection points are formed by node bodies. Rods and node bodies are connected to each other by pivot joints. Such node-rod systems describe an unstable state that enables spatial foldability as an inevitable mechanism. For applications in the field of structural engineering, foldable node-rod systems must be brought into a stable state. Various measures are available for this purpose:

1. Retrofitting stiffeners to joints after installation. If the forks at the end of the rod are designed in such a way that they allow elastic deformation of the legs, it makes sense to insert friction-enhancing washers between the contact surfaces of the fork and tongue, which are activated by the joint bolt, which in this case is a high-strength screw, and create the friction connection (Figs. 33, 34). The friction connection can also be established by making the knot body from a harder material than the rod connection surfaces. In this case, the inner surfaces of the fork-shaped working and connecting surfaces of the node bodies are grooved and press into the working and connecting surfaces of the tongue-shaped rod end when the hinge bolt is tightened (Fig. 35). Another measure to stiffen the joints in the installed state is to use fitting pins that are arranged radially around the joint bolt and pierce through the tongue and fork like the joint bolt. For a flat supporting structure, the radial holes in the tongue and fork are congruent. In the case of a curved structure, it is advisable to offset the ring of radial holes at the node by the angle that determines the curvature. To avoid having to install each shear pin individually, they are placed on a circular plate and installed simultaneously (Fig. 36). If the joint is formed by a shear sleeve, the plate on which the shear pins are located can be secured by a screw that is inserted through the shear sleeve.

2. Spatially foldable node-rod systems can be stabilized by having at least three foldable node-rod systems interact as a spatial truss. The upper and lower nodes of a partially unfolded node-rod system are connected to the nodes of two fully unfolded systems by a centrally located connecting bolt, with the first fully unfolded system forming the upper chords and the second fully unfolded system forming the lower chords of the spatial truss. A flat spatial truss structure made of half-octahedrons is composed of three link networks with a square module. A flat spatial truss made of full octahedrons is created by the interaction of two partially unfolded node-rod systems with two fully unfolded node-rod systems with a square module.

3. Spatially foldable node-rod systems can form stable support systems through shear-resistant connections with plates or plate-shaped elements. In this process, a partially

unfolded node-rod system is connected to a plate or individual plate-shaped elements at the upper and lower nodes in a shear-resistant manner. This creates multi-shell lightweight elements that are spatially stabilized by at least one partially unfolded network of members.

4. Finally, a partially unfolded node-rod system can be brought into a stable state by means of rope nets, which are tensioned in the upper and lower belt planes by rope clamps connected to the node bodies. The regularity of the polygons that form a link network is not a necessary condition for spatial foldability. Link networks with a diamond-shaped module or those with a module of shifted hexagons can also be folded spatially and assembled into spatial trusses in the manner described. This results in an unlimited variety of structures and their additivity. The unstable properties of spatially foldable link networks are of crucial importance for the prefabrication and space-saving transport of partially prefabricated systems. The link networks are only stabilized at the installation site and require a minimum of assembly connections. Only the measures described and their possible combinations turn unstable, foldable node-bar systems into structures of the highest effectiveness.

V Level Space frames

Space frames are effective supporting structures because they transfer loads in at least two directions and in one plane. Further advantages include the high degree of prefabrication of nodes and members, so that the elements only need to be bolted together on site. The ease of installation of the supporting structure with the technical building services units and the system-related elementization of the building envelope illustrate the ease of integration of these structures. Despite the advantages outlined above, space trusses are expensive and complex structures. The cost of assembling the systems often corresponds to the unit price of the individual parts. Compared to conventional space trusses, the assembly connections for a space truss consisting of foldable node-bar systems can be reduced to one-eighth. The upper chord plane forms a fully developed node-bar system, the diagonal plane a partially developed node-bar system, and the lower chord plane also a fully developed node-bar system. On the construction site, these components of the spatial truss are connected to each other in a shear-resistant manner by tensioning the node bodies. The node-bar systems are assembled as folded bar bundles (low space requirement, in the workshop) and transported to the construction site. There, they are “driven apart” by means of provisionally attached support wheels and prepared for connection with at least two other node-bar systems. Any necessary bracing of the upper or lower chord level can be achieved by means of a shear-resistant covering or by additional details not shown here. For multi-layered spatial frameworks made of foldable node-rod systems, mesh networks with square, hexagonal, and square and octagonal meshes are suitable. At least three node-rod systems are always connected to each other in a shear-resistant manner. The spatial foldability of all even-numbered polygons, as individual figures or as modular surface structures, leads to a multitude of structures that can be connected to each other and assume more or less stable states. The number of possible combinations increases immeasurably because polygons with unequal sides in pairs are also spatially foldable. Several of these structures are technically significant. However, the attached detailed drawings only address the technical usability of foldable square nets. It is obvious that the same applies to rhombuses, hexagons, and octagons.

VI Composite structures

Composite structures that use foldable link networks are characterised by a special design of the node bodies, which not only enable the articulated connection of the bars, but also provide a shear-resistant connection to at least one concrete slab that forms the upper or lower chord level in the supporting structure (Figs. 28, 29). The shear-resistant connection to the concrete is achieved either by means of head bolt dowels welded onto specially shaped node bodies (Fig. 30) or by means of special dowel or screw connections. In these constructions, the concrete slab can either be precast and continuous or consist of individual, partially prefabricated elements whose reinforcement is connected to the head bolt dowels, with the full load-bearing effect being achieved by a layer of in-situ concrete. With this construction method, composite structures can be designed as hollow-chamber, large-volume lightweight slabs for medium and large spans (Fig. 29). The cavity between the upper and lower belt levels is formed by the partially unfolded network of members, whose rods act as tension and compression rods and stabilize the lightweight hollow structure spatially. The cavity is ideal for installations and is also protected against fire and corrosion. It can be designed as an accessible installation space. This composite/lightweight construction method is suitable for building construction and civil engineering as well as for special constructions in the fields of hydraulic engineering, landfill technology, and offshore technology. It is also worth mentioning the possibility of under-tensioning a concrete slab using a partially folded network of links, whereby the composite effect with the concrete is achieved in the upper chord area by means of the detail already described, while the lower chord level is formed by a prestressed cable network that is attached to the node by means of special clamps (Fig. 32). Hybrid structures of the type described are effective load-bearing structures, primarily due to the specialization of their components: concrete in the compression zone, steel cables in the tension zone, and the prefabricated, foldable network of members as a diagonal plane.

VII Cable net structures

The development of highly durable materials on the one hand, and the possibility of geometric description and engineering control of complex spatial support structures on the other, has opened up a wide field for tension-loaded structures. In addition to high-strength steels for cables, there is now an advanced connection technology for cables, and finally, innovative membranes enable permanent space enclosures. Apart from questions of economic efficiency, the problems with structures subjected to tensile stress often lie in the considerable movements to which the supporting structure is exposed. Complex special constructions are therefore often necessary at the points of contact with other parts of the structure. Partially unfolded node-bar systems can stabilize rope nets. The upper and lower nodes of a partially unfolded link network are braced with a rope net (Figs. 31, 32). This creates stable, two-layer, tensioned membranes compared to single-layer nets. The shape of the node bodies is particularly well suited for bracing with rope clamps.

VIII Curved support structures

Flat lattice structures whose bars are connected to the nodes by pivot joints are in an unstable state, which enables folding as an inevitable spatial process involving all bars simultaneously. While the structure in its folded state represents the densest possible packing of the bars involved, in its unfolded state it can also be described as a net whose meshes are formed by compression bars that are connected to the nodes by hinges. For this reason, I would like to refer to the unfolded structure as a link net in the following. Under the influence of gravity, hanging models can be created from link networks that are either uniaxially or biaxially curved and, as a hanging structure, represent the inversion of an ideal compression arch or compression vault. By stiffening the joints, the suspended structure becomes a compression arch. It follows that a folded node-bar system can be transported to the construction site, unfolded there, initially lying flat, supported by assembly scaffolding and brought into the desired installation position, and that then, by stiffening the joints, a stable state, i.e., a supporting structure, is created. The advantages of this method are obvious: maximum prefabrication in the factory and elimination of adjustment and adaptation processes on the construction site. In this way, arch and dome structures, as well as hyperbolic paraboloids or freely curved structures, can be created. For constructions with larger spans and for structures with flat curvature, it may be advisable to design the construction in two layers (Fig. 37). In this case, the nodal bodies of two concentrically arranged member networks are connected to each other by a compression member to provide bending stiffness. This creates two concentrically arranged vaults that interact under bending stress. This structure can also be described as a double-layer lattice shell. Since the two shells, which are resolved into a bar lattice, are connected only by compression members that are perpendicular to the shell surface, the manageable geometry of the structure is complemented by a usable intermediate space that can be used for installations or as a ventilation zone in cold roof constructions.

IX Raised floors - suspended, integrated ceilings

Extensive prefabrication in the workshop and the elimination of tedious adjustment and fitting work during installation make foldable node-rod systems ideal for these applications as well. For a raised floor, a partially unfolded link network with a square module can be used, whose lower nodes can be adjusted to connect to the raw ceiling and whose upper points provide suitable support surfaces for square floor panels (Figs. 38, 39, 40). This type of raised floor would be particularly suitable for double floors subject to higher loads, such as in factory buildings: In a second variant of the double floor, the link network with square modules is fully unfolded and connected with vertical rods, which in turn are attached to the raw ceiling in an adjustable manner. In this case, the square floor panels have corresponding recesses and rest on the rods of the structure. For suspended ceilings (Fig. 41), unfolded link networks with square six- or eight-sided modules are primarily used. The unfolded link network serves as a template for the panels to be inserted. In this case, the foldable node-rod system can also be an integrated system, whereby the rods are designed to carry media or electricity. This creates a foldable pipe network that can be used for a variety of purposes, including as a sprinkler system (Figs. 41, 42, 43, 44). In a foldable node-rod system used as an electrical installation, the rods are designed as conductor rails that are connected at the nodes by flexible cables (Figs. 45, 46). Together with the panels inserted into the structure, this creates a light grid acoustic ceiling.

X Trade fair and shop fitting

Variability and flexibility, combined with the fastest possible assembly, are the hallmarks of successful trade fair and shop fitting systems. Foldable node-rod systems meet these requirements in a special way. Thanks to the highest possible degree of prefabrication, the structural connections that have to be assembled on site are reduced to a minimum. The multitude of geometric and structural possibilities, combined with the free choice of materials used, open up a wide range of useful structures. The geometrically optimized folding of flat node-rod systems and the shear-resistant connection of unfolded and partially unfolded node-rod systems to each other enables the formation of genuine spatial trusses from at least three prefabricated components. In contrast to known folding systems, these are structures that can transfer forces. It is also worth mentioning the possibility of conceiving a node-bar system as a foldable, grid-shaped electrical installation, in which the load-bearing bars are formed as conductor rails that are flexibly connected to each other at the nodes. Connecting an unfolded electrical installation grid with additional node-bar systems creates an electrically integrated spatial framework (Figs. 45, 46).

XI Miscellaneous
Now that we have discussed the possibilities in building construction in detail, I would like to list a few more applications for foldable knot-rod systems in bullet point form. I am thinking primarily of toys, leisure items, and furniture. Construction kits as models of foldable structures with appropriate color and material choices promote spatial imagination. Kites as foldable structures made of rods with textile covering are a particularly attractive way to utilize the foldability of surfaces. In terms of leisure equipment, I thought of rafts and bathing islands that have a structure as a foldable knot-rod system. Finally, in terms of furniture, an unfolded square grid can be doweled to the wall. Boxes with different compartments are then hung in the fields.

XII "Offshore Technology"
Platforms constructed on the open sea to enable the search for raw materials or to extract raw materials are visible elements of a new technology that serves the procurement of resources and is also referred to as "offshore technology." Transporting and installing these artificial islands is a major challenge in terms of what is technically feasible. One method involves prefabricating the entire drilling platform, which is then transported to the extraction site by several tugboats over a period of weeks. Large, foldable knot-rod systems, which are assembled at the shipyard in a bundled state from pipes with diameters = 1000 mm, could be loaded onto freighters and thus transported relatively quickly to the desired location, where they would be unfolded by tugs while floating in the water and then connected to other knot-rod systems to form a large space truss. The small number of assembly connections to be made at sea speaks in favour of this method compared to conventional solutions. The fully assembled platform can either be placed on the substructure using floating cranes or raised from there using hydraulic presses.

XIII Foldable knot-rod systems in space
Assembling conventional trusses in space is expensive and cumbersome. Any technology that simplifies this process represents a major advance. Not only does the number of assembly connections reduce to one-eighth compared to previous solutions, but the compact arrangement of the nodes and rods when folded also makes foldable node-rod systems ideal for use in space. In addition to the obvious advantages in terms of transport and assembly, the link networks can be unfolded easily under weightless conditions. Nodes and rods for these applications can be made from special composite materials that are lightweight and dimensionally stable even under extreme temperature differences. Space trusses in space are necessary platforms for various purposes and form the structural basis for larger space stations that enable humans to stay in space for longer periods of time. They are a crucial component of space technology. Folding and unfolding is basically the only effective strategy for overcoming the "eye of the needle" of gravity with larger structures.

XIV Foldable structures in nature
In the preceding chapters, I have dealt with the technical applications of foldable node-rod systems. In the last chapter, I would like to leave engineering science behind and address the question of whether the principle of spatial foldability of modularly arranged surface

structures could play a role in nature. The following speculative questions posed by a layman are directed at physics, chemistry, and biology. First, it is obvious to want to explain the lattice-forming properties of spatially foldable surface structures, e.g., the structure of crystals. How does a crystal grow? What state of aggregation do the elements involved assume? Is it possible that the elements first constitute themselves in a surface structure and then form a lattice with other surface structures? Can the different physical and chemical properties of a compound be understood as a selective solution of the lattice bonds of a structure? What influence do electrically positive and negative charges have in connection with the “high and low points” that arise during the spatial folding of a modularly arranged surface structure? Based on the assumption that the processes of living nature are also structurally organised and obey morphological laws, further questions arise. Metabolic processes as the energetic basis for growth, movement, division, and sexuality are characteristic of living beings. Plant and animal life are interwoven through a diverse network of relationships. Animals and plants, in turn, could not exist without the exchange of matter with so called inanimate nature. It is a material reservoir and spatial reference system for the evolutionary development of living beings. Although every natural science is committed to finding the truth—saying nothing more than what can be said in the sense of scientific reasoning—this is the principle of all scientific activity. Nevertheless, the goals and content of research change. On the one hand, bound by method, on the other hand, dependent on operational means, the search for truth or the unraveling of the world is only possible to a certain extent. Furthermore, there are dependencies on the respective social context. Which worldview should be underpinned by research? These questions are important here insofar as it should be noted that the focus of today's research is on structural issues and not, as in the past, on the phenomenological description and classification of things and living beings. It is not so much the divisive factors that manifest themselves in, for example, species-specific phenomena, but rather the commonalities that can be recognised in the structure that are the focus of attention. Orders, rules, structures, systems, and processes are being discovered everywhere. We are in the process of deciphering the grammar of the world. In some fragments, this may already have been achieved. The periodic table of elements, for example, is a self-contained and convincing model of structural order. Organic chemistry and biochemistry have also demonstrated this structural order for central processes of living nature. The identical reduplication of deoxyribonucleic acid as the carrier of genetic information in the kinetic structural model of a double helix represents a milestone in scientific knowledge. Ever new discoveries about the chemistry of substances force us to revise our current models. Structural models that are capable of capturing different states of one and the same molecule and thus explaining seemingly incompatible properties of a chemical compound are increasingly coming to the fore. The cell, the smallest unit of living organisms, is formed by macromolecular structures whose chemistry determines the metabolic processes, divisibility, and function of the cell in the organism. In order to understand these processes as lawful sequences, it is necessary to conceive of molecular structures as spatial volumes.The model concepts of these volumes would then have to be examined in terms of their binding capacity, their mutability, and their kinematic properties. How can one explain the selective permeability of a cell membrane, or the processes involved in cell division? Admittedly, these questions are far removed from any engineering science. On the other hand, the discovery of the spatial foldability of modular surface structures encourages us to describe their extremes as maximum unfolding and densest possible packing, to examine their unstable states as kinematic processes, and to discover their stable states as modular interactions between several surface structures, but also to search very specifically for correspondences in nature. In conclusion, I would like to express the hope that the structures shown here, beyond their technical applications as node-rod systems, may be of service to the natural sciences.