Transformable Structures for Mobile Shelters

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Mobile shelter systems are a type of building construction for which there is a vast range and diversity of forms, structural and construction solutions. They are designed to provide weather protected enclosure for a wide range of human activities. Enclosure requirements are generally very simple, with the majority needing only a weather protecting membrane or skin supported by some form of erectable structure. In all applications, both the envelope and structure need to be capable of being easily moved in the course of normal use, which very often requires the building system to be assembled at high speed, on unprepared sites. Structures can vary in scale from the smallest 6.0 metre span tent to 50 metre plus warehouses designed for storage and aircraft maintenance at the other. Consequently, design requirements vary considerably with application and size of enclosure. [Burford & Gengnagel 2004]

Some of these systems contain very basic, inexpensive structures, having been derived from conventional building technologies. However, alternative solutions have been developed that adopt sophisticated structures and deployment mechanisms contained wholly within the systems structure with no requirement for cranes and large plant for their erection. Design innovation in the use of new materials, detail design and new structural forms may be found in almost all areas of application and at all scales of enclosure, making this a very rich field in alternative construction ideas and technology. One area that merits particular study is those structures that are themselves transformable and can change their form from one state to another state or form and where the structural system is changing from a kinematic to a statical system.

Figure 1. concept model for a mobile grandstand canopy with a transformable supporting structure based on a cantilevered truss with a highly elastical compression member,
[Burford & Gengnagel 2004]
A transformable structure is a primary structure that is able to change its function from a mechanism to a statical system and the geometry of its form. As a statical system it distributes the applied loads and self weight of the construction. As a mechanism it gives the construction the ability to reversibly change its form from one geometrical state to another.

In mobile shelter systems this normally means that the structure will change from a largely non-space defining form into a two- or three-dimensional space enclosure. In almost all transformable systems, it is the main structural element of the primary structure that is responsible for giving the construction the ability to transform. When the transformation is complete, the whole system is fixed at its supports in order to stabilise the soft or moveable components of the structure.

Transformable structures can be classified by the process of form-change in relation to the internal strain, which provides three principle Groups. ‘Fig.2’ One group are structures containing rigid pivoting elements. For these systems, geometrical changes do not produce internal strain. Another group are structures of elastically rigid elements, that develop internal strain during their transformation. The third group are structures of soft elements, such as membranes, without bending stiffness that allow geometrical changes, producing either no or minimal internal strain. [Gengnagel 2005]

![Figure 2. an arch as a transformable structure, a. comprised of rigid pin-jointed elements, b. comprised of a elastically rigid element c. comprised of a soft element (e.g. membrane)](image)

Type 1 and 2 systems are predominantly based on rigid, bending resistant members that are connected to each other by pins. Chain systems are the most basic of these and contain a minimum of two rigid members pinned at B and pivoting about support C. Support A is free to slide in a horizontal direction. For type 1 a vertical force F applied at B in a vertical direction is used to initiate the transformation. The system has the advantage that elements can be added to the chain as it is erected thereby making it possible to erect the structure within the footprint of the final deployed enclosure form. Additionally, the forces required to erect the system are lower than the previous example as only a vertical component of force is required to initiate the mechanism.

For Type 2 a force F is applied at A which produces a moment about A and producing a displacement of B towards C, causing a displacement of B in a vertical and horizontal direction. Members of the system are first connected on the ground in a horizontal position prior to the erection. This mechanism can be used in pin-jointed and bending frameworks, portals,plates and arches. In arches curved members or multiple, short, straight members can be used which are assembled in chain type configurations.

Type 3 systems contain a minimum of two rigid members and a third telescopic member. Member a is pinned at support A. Support B is free to slide in the horizontal direction. Members b and c are pinned to each other at C. Assembly b/c is attached to a pin at A and B. An outward horizontal force applied at B produces a horizontal displacement in the direction of B which causes C to move horizontally and vertically in a downward direction. The mechanism contained in member a may be initiated by hydraulic pressure or a mechanical system.

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Figure 3. Matrix of Transformable Stuctures for Mobile Shelters

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Type 4 systems are pivot-jointed rigid systems containing two rigid members a and b which are connected at B in a scissors arrangement. Each member a/b needs to continue through the pin to transmit bending to either side of the joint to maintain stability. Assembly a/b is reflected about the vertical axis and connected at pins C and E producing a quadrilateral form having all sides equal length (linear/flat scissor arrangement) or two sides equal length (linear/curved scissor arrangement). The assembly is pinned at support F and free to slide in a horizontal direction at support A. An outward horizontal force at A reduces the vertical distance between C and E while increasing the horizontal distance between B and D in the opposite direction. This has the effect of extending the system in the horizontal direction. The mechanism may be used in one-dimensional, two-dimensional and three-dimensional curved structures. The global structural behaviour will be either a bending frame, arch or shell. It can be used as a combination of linear rigid and soft surface elements or pivoting rigid plates. The individual members of the system transmit applied loads in bending which means that structures using this mechanism tend to be less efficient than axially loaded structures.

Systems of Type 5 containing an element or system of elements that are free to slide along a predefined path. The path can be linear or curved, stiff or soft. A basic system consists of a single member or assembly that may be rigid or soft a, with two fixed pinned supports at A and B. This is attached to another member b by one or more sliding connections C. The displacement F should ideally be applied along the axis of the path a.

System 6 containing a minimum of three rigid members which combine pinned and sliding connections. One member a is pinned at supports A and B and members b and c are pinned to each other at C. Assembly b/c is attached to a by a pin at B and a sliding connection at D. A vertical displacement applied at D produces a vertical displacement in the direction of B which causes C to move outwards and upwards. This mechanism is commonly used in umbrella type systems.

Systems of Type 7 contain flexurally rigid members that develop internal strain as a result of the deployment. A basic system comprises a single, flexurally rigid member, or a system of multiple members rigidly connected. The member is pinned at support B and free to slide in a horizontal direction at support A. An inward force at A produces a moment and rotation at support B which causes it to flexurally deflect upwards into a curved form. The deflected profile during the deployment varies depending on whether a moment is applied to both supports or just one. The deployment may also be initiated by a vertical upward force in the centre of the member. The mechanism can be used in two-dimensional and three-dimensional structures such as arches and shells.

Systems of Type 8 contain a surface such as a membrane which has no resistance to compression forces. Surfaces can be thought of as a finely discretized cable mesh comprising very short bars or links with pinned connections having 360 degrees of rotational freedom. The surface has to be a soft element. Mechanically prestressed surfaces are deployed by applying outward forces along the boundaries or at corners of the surfaces and at areas or lines within the surface. Surface forms may be flat, or curved in two opposite directions. Mechanically prestressed surfaces rely on an additional rigid structure to develop and maintain their three-dimensional deployed form. The surface can be described as the main primary structure where the surface itself is responsible for defining the internal shape or form of the enclosure and the rigid structure has no space defining sectional properties, e.g. a mast.

Systems of Type 9 are air pressurized surfaces comprising either a single surface that is sealed around its perimeter to the ground or two surfaces that are joined around their perimeters. Air pressurized surfaces are deployed by increasing the internal air pressure of the enclosed volume causing the surface to move radially outwards.

The variations of transformable primary structures are generated by comparing the main structural system types with the transformable system types. One of the oldest forms of transformable structure is the umbrella, developed as a form of personal transportable weather protection. However,
adaptations of this basic mechanism have been used in applications ranging from small scale space enclosing camping tents to comparatively wide span canopies such as the Pink Floyd, USA Tour and The Prophet’s Holy Mosque, Madinah, Saudi Arabia. In most systems the umbrella mechanism is used as a modular canopy supported by a central column which contains the mechanism for the cantilevered, radial, folding arms. This produces a planar roof without enclosing walls which has the ability to extend in two or more directions. It is normally limited in this respect by the problems of forming and weather protecting the junctions between adjoining modules. Additionally, the system relies on a single column and moment resisting connection to the ground which tends to limit its span due to the foundation requirements. The basic mechanism has been adapted for closed form systems where the arms or legs have been extended to the ground thereby providing a second means of support to the central column. Rectilinear, volumetric systems tend to be limited in their ability to transform and so there are only two principal variations. A rectilinear volume can be transformed to a non-space enclosing volume by collapsing the module in on itself. This can be achieved by using hinged connections along the connecting edges of orthogonal panels and / or in the centre of two of the panels so that the panels can fold inwards. A fixed rectilinear volume can expand outwards using a similar mechanism or by sliding walls or roof planes, outwards along predefined paths. Pole supported mechanically prestressed membranes can be used in a variety of regular and free-form plan shapes and may be produced in an equally wide variety of three-dimensional forms. These can range in scale from the smallest single pole supported camping tents to very wide span multiple pole supported marquees such as the RSSB Shelter. Internal air pressurized enclosures have a limited area of application due to the problems of maintaining a large pressurized volume of air. However, in small scale applications skin or air-beam pressurized systems are widely used in applications where very rapid deployment is an issue. These systems have the advantage of being lightweight and low bulk. A drawback is the requirement to have some form of powered generator to pressurize the structure. By far the greatest diversity of transformable structures combine pinned / sliding elements or flexurally deformed elements in frames or arch primary structures. This produces a range of primary transformable structures that may be principal hierarchical elements of a primary structure or principal structures of a non-hierarchical structure. Consequently, structures may expand in two or three directions and can be packed into small areas or simply flattened to a non-space defining form. Mechanisms and systems are used at all scales of enclosure. However, flexurally bent mechanisms are limited in span unless a second system of restraint is used.

The study shows that there are a far greater number of transformable mechanisms that could be applied to different principal structural elements which produces a wider range of primary transformable structural systems. Although a number of current shelter systems utilize innovative transformable structures, these are comparatively rare in practice. Furthermore, there remain significant potential in further exploring the relationship between the alternative possible transformable mechanisms and shelter constructions. This area of mobile shelter technology is potentially very important, having the widest possible impact both within the specific area of mobile shelters and in wider building construction applications, such as retractable roofs or adaptable facades.

References


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