Tents: The State of the Art in Deployable Shelter

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INTRODUCTION: DEPLOYABLE SHELTER FROM PRE-HISTORY TO DAVINCI AND TODAY

Tents have been a primary form of human shelter, especially for nomadic cultures, hunting parties and military expeditions, for as long as we have records of human activity. Cave paintings supply the earliest evidence of tents dating to the Cro-Magnon period in Europe, ten to twenty thousand years ago.[1] Although nomadic peoples have largely disappeared, the plains of Eurasia still host numerous bands of yurt-dwelling shepherds who utilize traditional portable shelters. In antiquity, tents came to occupy a central role in the rise of empires and in the development of numerous cultures. The basic unit of the Roman legions was the *"contubernium,"* a party of eight men sharing a tent and a packhorse.[2] The description of the portable temple contained in the book of Exodus might serve as the archetypal description of tent technology spanning the period from biblical times until very recently.[3] In almost every recorded example, tents consist of a loose assemblage of posts with layers of fabric skins held taut by lines or cables in tension.

Historical evidence of attempts at innovation in the area of tents and temporary structures is sparse at best. Leonardo Da Vinci's more than 5000 pages of extant drawings record studies of everything from human anatomy to flying machines, siege engines and churches. The collection *"Manuscript H"* contains some of his few known sketches for tents or portable shelters.[4] One view seems to show a system for rapidly raising a fairly traditional tent with a tension cables set in a ring. (H1, foglio45r) Another shows a three-dimensional view and details indicating a framework that is foldable with hinges and a locking mechanism (H2, foglio 30v, 31r) as seen in Figure 1. It is unlikely that either the tent or this structure, described simply as a "padiglion" (pavilion) was intended for emergency use. It is clear however that DaVinci is speculating about systems of deployment that would be far more self-contained than a traditional tent's assemblage of loose parts. These proposals for more highly integrated systems may well be the first example of what we would today call self-contained, rapidly deployable shelters. Unfortunately, no other graphic material exists to help further explicate DaVinci's thinking, and as with nearly all but the most recent deployable structures, no physical evidence of any kind remains. Beyond these investigations, there is little evidence of efforts to significantly transform age-old approaches to tent design until well into the 20th century. Why has the tent proved to be such an enduring solution and why has innovation been so rare?

ARE TENTS THE BEST STRATEGY FOR DEPLOYABLE SHELTER?

The example of history indicates that the tent, in one form or another, has long been the most widespread solution to the problem of deployable shelter. Prior to the 20th century, it is nearly impossible to identify any other significant approach to the problem. In general, tent construction offers numerous advantages, among them: simplicity, extreme portability, and economy of means. Tents are easy for individual users to carry, construct, modify if necessary, and maintain. Of course tents also suffer from numerous drawbacks in comparison with other possible systems, including relative structural instability in severe weather and very limited thermal performance. Since expeditions, wars and emergencies are generally hoped to be

Figure 1 - Roman military tents from the Column of Trajan (L) and details of folding pavilion Leonardo Da Vinci, Manuscript H (R)

temporary situations of extremity, little interest has traditionally been focused on comfort or longer-term durability. But as wars, man-made and natural disasters and their associated population displacements become more widespread and their effects longer lasting, rapid shelter technology needs to respond with better performance.

Do other deployable systems rise to the challenge of offering higher performance shelter than tents? Panelized, flat-pack or folding systems, like that shown in one of DaVinci's sketches, offer some advantages because they are potentially more stable and durable than tents. By virtue of their more robust construction, they also offer the possibility of more complex layered enclosure systems for potentially better thermal performance. The disadvantages of panelized systems seem to be their increased complexity, higher costs, greater risk of construction difficulties and more limited portability. In recent designs, the desire to alleviate some of theses disadvantages has produced mixed results. For example, the Global Village Shelter (GVS) by Ferrara Design, is the most widely heralded new approach to deployable shelter.[5] It is a flat pack system of custom shaped plastic-impregnated cardboard panels that assemble like a large box, approximating the shape of a small hut. While this system, intended to last for 18 months, is marginally more durable than a good tent, its structural geometry, like a house of cards, is highly inefficient. Further, the GVS still requires the addition of plastic tarps to waterproof the roof. Perhaps the greatest advantage of the GVS is its comforting domestic appearance. Beyond that, it offers scarcely any more stability, insulation or flexibility than existing tent designs.

Because the western culture of mobility is typically associated with automobiles or aircraft, it should not be surprising that approaches to deployable shelter have also taken a vehicular track. Campers, trailers, and hybrids like pop-ups all share the distinction that they are based on a fixed chassis on wheels with much or all of their enclosed volume delivered in finished form. The advantages of vehicular systems are that they are potentially the most stable and durable approach to deployable shelter, and they offer the possibility of the most complex layered construction for potentially the best thermal performance. The disadvantages, however immediately outweigh the advantages for most situations, because they are the most costly, least efficient to deploy, and least flexible in their use. As the FEMA trailers of hurricane Katrina so clearly illustrated, campers are slow to deploy in large numbers, expensive, wasteful of resources, and far from user-friendly. Although they might be the longest lasting option, compared with their high cost, they are uneconomical in the extreme.[6]

It is still the case that the most advanced military forces in the world rely on tents not only for immediately deployable and temporary shelter, but as is the case with the Persian gulf wars, also as long term housing for personnel. The only innovations evident in today's military tent-cities appear to be the adoption of a semi-circular 'Quonset hut' form for simplicity and structural integrity, and the addition of hugely wasteful air conditioning systems. According to a Louisiana National Guard unit, typical army tents of today: "…measure about 100 x 25' long and sleep 60 people cot-to-cot. As tents go, they are comfortable and robust. About every third cot there is a heating/air conditioning unit."[7]

In the civilian sphere, the two largest organizations engaged in global disaster relief are the United Nations (UN) and Oxfam, and each agency's long-standing choices for deployable shelter are noteworthy. In response to both natural disasters and long-term population displacement, Oxfam has maintained a policy of stockpiling corrugated sheet metal for quick delivery to affected areas. Local inhabitants and aid volunteers are then free to flexibly deploy this economical material that combines structural stiffness with basic moisture protection.[8] The UN has long preferred supplying simple 13 by 16 foot blue plastic tarps, for similar reasons of simplicity, immediacy, cost-effectiveness, and flexibility. In fact, in current practice, even tents are judged to be too complex by these agencies. According to the UN High Commissioner for Refugees *Handbook for Emergencies*:

> "Except for tents in certain circumstances, prefabricated or special emergency shelter has not proved to be a practical option on either cost or cultural grounds… Refugee housing should be culturally and socially appropriate and familiar. Suitable local materials are best, if available… (and) Wherever possible, refugees should build their own housing…" [9]

Given the priorities and attitudes of these agencies, it is nearly impossible to imagine any system more complex than a tent gaining widespread acceptance. Their insistence on flexibility and the importance of hybridizing the supplied systems with local materials and ingenuity are also key concepts for future deployable shelter designs. Given the inherent drawbacks of panelized and vehicular systems, the tent appears to remain the most likely model for the provision of immediate shelter in humanitarian applications. Rather than trying to make flat-pack or vehicular systems simpler, more affordable, less complex, or more adaptable; the best approach for higher performance rapid shelter seems to be the making of better tents.

EMERGING DEVELOPMENTS IN TENT DESIGN

Analysis of emerging trends in the areas of military research and civilian innovation in tent design reveals new potential directions for the creation of higher performance, but still practical tent technologies. In military engineering, relatively little attention has been paid to housing as opposed to other more specialized needs like mobile hospitals and the protection of supplies and delicate machinery like aircraft. The US military performs most of its deployable shelter research at the Natick Soldier Center in Massachusetts. Their work is closely tied to parallel and collaborative efforts in private industry and academic research institutions. While non-military research into deployable shelter systems has been sponsored by aid agencies in the past, the bulk of contemporary work in this sphere is independent and speculative. Cutting across the boundaries between these different research initiatives, two clear and promising directions are evident: advances in structural systems and the development of new tent fabrics.

FORMAL AND STRUCTURAL GEOMETRIES

A basic rectangular plan shape with some sort of triangular roof pitch has long been the most common structural geometry for tents in the western world. This form has its roots in both traditional house forms, and also in the rectangular shape of the woven fabrics produced on hand- and machine-operated looms. Since the basic cladding material often comes in rectangular pieces, the most labor efficient way of producing tents has long been to use these raw materials in rectangular layouts. Civilizations that produced tents primarily from animal skins or felted, as opposed to woven, fabrics, have tended to maintain circular plan forms. In Native American building cultures, examples of round teepees and wigwams far outweigh what little evidence there is for rectangular tent forms.[10] On the Eurasian plains, nomadic shepherds construct yurts made of rings of bent saplings clad with thick felt. These structures are so sturdy that rather than being disassembled for transport, they are often lifted and moved intact on the back of wagons.

The inherent structural rigidity of circular forms as compared with rectangular ones is fairly obvious. Yet, modern attempts to revive circular forms for deployable shelters in both civilian and military applications, like Buckminster Fuller's Dymaxion Deployment Units, have failed to gain wide acceptance. Fuller's later Geodesic Dome research sought to combine circular plan and semi-circular cross section shapes with the rigidity and repeatability of triangulated systems. Although this approach found a receptive audience in the US Military, and numerous proposals were publicized showing his domes being deployed by helicopter for every imaginable purpose, its use in practice was limited largely to the protection of radar equipment in arctic deployments.[11] The drawbacks of Fuller's dymaxion system for rapidly deployable shelter appear to have included the number and complexity of joints between structural elements, and the complexity of cladding the dome.

In contrast to circular plan forms, semi-circular roof shapes have fared much better. Although there is evidence of curved or arching tent roof

Figure 2 - Global Village Shelter by Ferrara Design (L) and Geodesic dome pavilion at Vitra (R)

forms in some Native American cultures, it was the US Navy's civil engineering battalions, based in Quonset Rhode Island, who popularized this efficient roof form during world war two.[12] The 'Quonset Hut,' widely deployed as a semi-permanent building with rolled corrugated metal serving as both structure and skin, is also the model for the shape of most contemporary military tents. The advantages of the Quonset hut lie mainly in its formal simplicity and its inherent structural stability. It is also a shape that accords with culturally preferred rectangular plan forms, and that is capable of being made relatively simply from rectangular materials.

Research in the basic structural shapes of tents has focused primarily on arched, domed or semi-domed structures that employ some amount of double curvature to increase structural stability. The "Quonset hut" form, composed of a simple half cylinder, employs only curvature in one direction. Generating anticlastic double curvature for stability in tensile structures has been the subject of both civilian and military research for several decades. The hyberbolic paraboloid form, a structurally stable form of double curvature produced by opposing upward and downward forces maintained in balance on diagonally opposite corners of a stressed fabric, is popular for shading structures, but has found few applications in deployable shelters largely because of the need for heavy anchoring points to resist the high tension stresses induced in the system. New research in fabric structures is focusing on ways to generate a second direction of curvature for structural stability in designs based on a simple rectangular arched form.

By inducing curvature perpendicular to the arches, a sort of hourglass or scalloped shape can be generated in the typical Quonset hut form. This approach puts greater stress on the arches that define the overall cross sectional shape, but solves problems with lateral stability along the length of the cylindrical form. Work in this area, along with basic research into the performance of fabric tension arches and other deployable tent morphologies, is being performed by the Lightweight Structures Unit, a collaboration between the Berlin Kunst Institut and the University of Dundee in Scotland.[13] One good example is their recent work on a new shelter system sponsored by the UK Ministry of Defense, described by the researchers as a:

> *"…very lightweight, rapidly deployed, small to medium size shelter system (that) uses as the principle structural member, a transformable fabric web braced arch to support a double curved mechanically prestressed membrane skin. The resulting truss is reversibly transformable from a linear flat state to its erected two-dimensional form due to the elastic bending of the rib… The truss provides the basis for a very stiff, lightweight, foldable structure, packable to a small volume."*[14]

Their approach seems particularly promising because it is a hybrid, combining a simple arch-supported Quonset hut shape with highly advanced solutions for the arch structure.

Their design also generates double curvature in the fabric between the arches, thus assuring greater overall rigidity and stability.

MATERIALS RESEARCH BOTH FOR STRUCTURE AND ENCLOSURE

For millennia, tent materials have consisted of compressive frame elements, tensile strands for stability and integrity, and pliable skins for enclosure. Frame materials have ranged from animal bones in early examples, to the predominance of

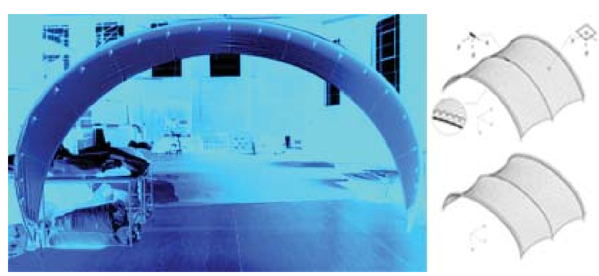

Figure 3 - Lightweight Structures Unit research: Fabric web braced arch (L), Studies of double curvature morphologies (R)

wood in most cultures.[15] Tensile forces have been handled by animal products or twined fibers in the form of ropes. Twentieth century developments have substituted steel, aluminum and fiberglass for compression, and steel fibers or plastics such as nylon for the tensile elements. Further developments have involved the creation of lightweight metal trusses for structural spans or arches.

Recent research sponsored by the Natick Soldier Center has also focused on ways to quickly deploy more traditional metal arches by combining hollow metal truss tubes, hinged together with stressing tension cables that run through the bottom (inner) chord of the arched truss. Working together with a stretched tensile skin, this kind of system can almost literally unroll to produce a sturdy structure that is very lightweight, but made of incredibly intricate and complex assemblies.[16] In the civilian sphere, Chuck Hoberman's far more elegant and even more complex deployable and transformable shelter systems based on scissor mechanisms, represent the state of the art in mechanically unfolding space trusses and geodesic domes.[17] All of these avenues however, seem to lack the important aspect of structural simplicity that has always been central to tent design. Because of its simplicity, the Lightweight Structures Unit's previously described fabric arch research seems more promising in the area of arched truss design.

An alternative approach, also being undertaken by the US Military and its suppliers, involves the replacement of structural metal arches with inflated fabric tubes called "air beams." Once filled with compressed air, the air beams do not need constant replenishment, and the pressurized elements form a framework that is clad with a loose fabric enclosure.[18] Although materially efficient, these air-beam tent systems require highly specialized fabrics designed to hold high air pressures without leaking or being threatened by punctures.

The general concept of site-filled fabric containers gets an interesting twist in the work of Iranian-born California architect Nader Khalili. One of his inventions, called "Super Adobe," consists of fabric tubes that are filled with earth and stacked in spirals to form earthen domes.[19] Each layer is secured to the previous by barbed wire placed in between to act as mortar or nails. The overall system derives its stability from the circular domed form, and the architect recommends adding a further layer of local material to weatherproof the exterior. Due to its thermal mass, this system is well suited to warm climates, but Khalilli claims that the system will also work well when filled with snow. Although based on deployable fabric elements, this system is clearly not a tent per se. It does however represent a much more durable approach that gives priority to local materials and involves end users quite directly in its construction. Super Adobe's major drawback seems to be the amount of time necessary for deployment, making it more useful for the longer-term housing of displaced people than as a rapidly deployable emergency shelter.

With the possible exception of Super Adobe's thermal mass, the major drawback of all tents is the inefficiency of fabric as a large scale environmental enclosure. Traditional tents are based on local materials and systems developed to work with particularized weather conditions. In cold climates, furs or heavy felts were used while around the Mediterranean, light colored breathable fabrics like linen predominated. Early modern developments involved the use of waxes and other treatments to improve water and wind resistance and other treatments to provide fire resistance. New materials offer a much wider range of environmental responsiveness.

Directionally selective materials that are chemically similar to GoreTex but are also fire retardant, like ToddTex and Tegraltex, can maintain water resistance from outside while allowing the release of water vapor from inside an enclosed space. New materials have also begun to offer improved thermal insulation by reflecting unwanted radiant heat away in hot climates or keeping heat reflected to the inside in cold weather. Here again, promising new research is under way at the Natick Soldier Center. A simple camoflaged tarpaulin intended as a temporary shelter and concealment for forward scouts and snipers not only protects soldiers from the elements, but also hides their 'thermal signatures' from enemy sensors. Although details of the material innovations of the "Stealth Surveillance Shelter"[20] remain classified, this research might eventually lead to much more thermally resistant fabrics for civilian uses.

Yet no matter the insulation value of a single layer of fabric, achieving the kind of sophisticated environmental responsiveness possible in layered building skins of greater mass and thermal resistance will remain a difficult challenge for deployable shelters. For moisture control, civilian tents have long featured double walled designs with a fully vented airspace between waterproof outer and breathable inner layers. But this controls moisture only, giving little if any additional thermal benefit. By capturing multiple layers of air, and effectively managing the transmission of thermal energy between those layers, the performance of even the most thermally insulating fabric can be greatly improved.

An interesting approach to thermal adjustability was developed in the 1960's but has yet to be widely tested. Developed by Nikolaus Laing, this concept involves a low-pressure pneumatically inflated skin that contains multiple sub-bladders capable of selective inflation in order to maximize solar shading or solar gain depending upon local climatic conditions.[21] Inner bladder surfaces of differing opacity can be opened or closed like venetian blinds against either the inside or outside surfaces in order to adjust the penetration of sunlight into the airspace. With the outer surface shaded, sunlight is reflected away and the bladder becomes a cool insulating layer. With the inner surface closed and the outer one open to sunlight, the bladder works as a greenhouse, trapping warmth in the airspace in cold climates. This kind of thermally selective system, although somewhat complex and as yet untested, might serve as an inspiration for the kind of innovations needed in order to further improve the thermal performance of tent enclosure systems.

Finally, with new developments in photovoltaic and battery technologies, it is possible to imagine tent fabrics that can serve not only to control thermal gains and losses, but that can also produce useful energy. The "portable light project" a collaboration between architect Sheila Kennedy, textile designers, and the electronics industry, has resulted in a prototype for a simple and durable source of light, powered entirely by flexible photovoltaic panels sown into a fabric handbag.[22] According to the project's website:

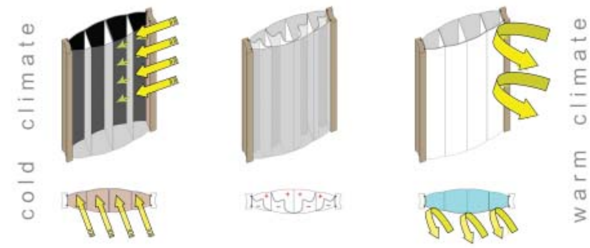

Figure 4 - Thermally responsive low-pressure pneumatic skin, invented by Nickolaus Laing

> "The remarkable energy efficiency of high brightness solid state lighting (HBLEDs) means that a bright digital light of 80 lumens per watt (bright enough to read, work and illuminate areas at night) can be produced by a single miniature diode and powered by small areas of flexible photo-voltaic (solar) panels."[23]

It is clear that this emerging technology could easily be integrated into the fabric of deployable emergency shelters intended for devastated areas where infrastructure, whether preexisting or not, would be unable to provide power for lighting or other necessary uses. It should not be surprising that the military is also following up on this area of research, including research into weaving the photovoltaics directly into the fabrics themselves in the form of photovoltaic fibers, a unique breakthrough for dye-sensitized nanocomposites.[24]

CONCLUSION

For millennia, the tent has been the most widely employed solution for rapidly deployable shelter. Although different forms like the yurt or the teepee are identifiable, the basic approach of using a lightweight framework to support some sort of a fabric skin, has always been maintained. Among the major benefits of tents are their simplicity, portability, adaptability, and cost-effectiveness.

Figure 5 - Portable Light Project (L) and first generation flexible photovoltaics in military tent applications (R)

Although tents have been gradually adapted over centuries to better serve highly localized environmental conditions and cultural needs, there is little evidence of significant innovation even throughout the first half of the 20th century. New research in improved structural systems and higher performance enclosure systems have produced isolated results but no wholly new approaches to tent design have yet to emerge. Perhaps the state of the art in tent design will be revolutionized by hybrid approaches that combine efficient structures with thermally responsive and energy producing skins. Although there are numerous possible responses to the growing need for better deployable shelters, the inherent simplicity and portability of the tent, combined with provocative ongoing research initiatives, are clear indications that the future of rapid shelter is likely to come in the age-old form of a tent.

ENDNOTES

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24. http://nsc.natick.army.mil/media/fact/shelter/FlexPhoto.pdf