

TENT-SEGRITY

by  
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B.S. Stanford University  
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ABSTRACT

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Submitted to the Department of Architecture on June, 1977  
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degree of Master of Architecture.

The intention of this thesis is to investigate  
possible impacts of tents on building form. Four  
forms to be studied are:

1. An extra environmental barrier which might  
protect the interior home in winter, be an expanded  
version of a porch, verandah, or hisashi in the  
summer, or be taken down if desired.
2. An impermanent addition permitting growth  
and contraction of a house to meet a family's  
changing needs over time.
3. An easily constructed roof which defines an  
order for an initially incomplete house to be  
finished incrementally.
4. A soft connection between units of a complex  
of buildings.

Thesis Supervisor: \_\_\_\_\_  
Edward Allen

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I wish to dedicate this thesis to those people whose help and encouragement is gratefully acknowledged:  
to Suzette and the Little One,  
my father and mother, Raymond and Eliot,  
Ed Allen, Tunney Lee, Jim Becker, and Rene Mugnier,  
and to Chip, Mark, Kevin, Gail, and Denice.

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## DEFINITION: TENSEGRITY

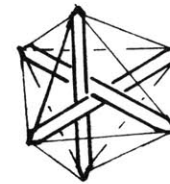
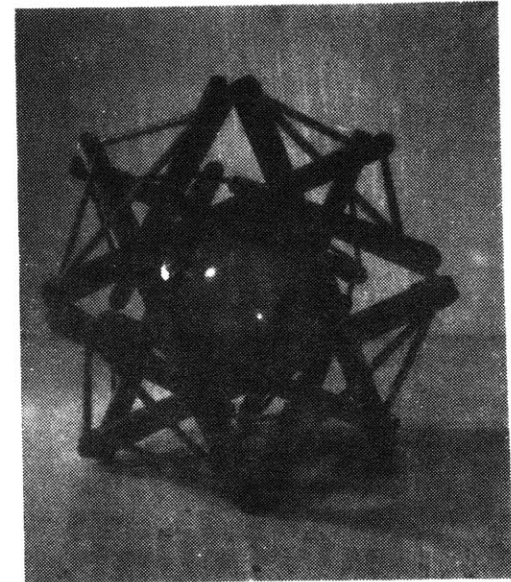
"The word 'tensegrity' is an invention: it is a contraction of 'tensional integrity'. Tensegrity describes a structural-relationship principle in which structural shape is guaranteed by the finitely closed, comprehensively continuous, tensional behaviors of the system and not by the discontinuous and exclusively local compressional member behaviors. Tensegrity provides the ability to yield increasingly without ultimately breaking or coming assunder."

--R. Buckminster Fuller  
Synergetics

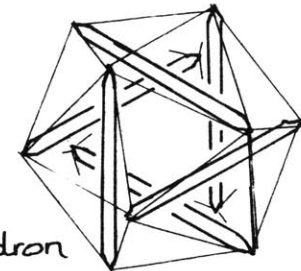
## PRINCIPLES OF TENSEGRITY DESIGN

Tensegrity is a building system which offers many references, vocabulary, design clues and construction possibilities that have not yet been exploited. The clues to these applications lie in the nature of the tensegrity system in general and the t-octohedron and t-icosahedron in particular. Therein lies the basis of this thesis.

What is so special about this system? Tensegrity is a structural concept in the realm of funicular structures, i.e., structures which do not resist loadings by means of bending stresses. It is a



the t-octohedron

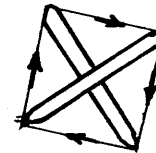


the t-icosahedron

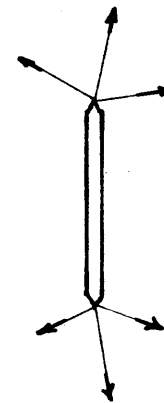
synergetic network of members acting in either pure compression or pure tension, somewhat like a truss. But unlike a truss, none of the compressive members are directly connected to one another. The end of each strut (compressive member) is restrained by a minimum of three strands (tensile members) and the push from the other end of the strut. This is the case because the system acts synergetically; each member is dependent on the forces acting in each of the other members in the network for its own stability. The visual impact of this is intriguing if not confusing. The structure appears to contain sticks floating in space but held rigid by almost invisible strands.

The three dimensional forms which can be constructed following tensegrity principles include the tetrahedron, the octahedron, the cube, the icosahedron, and the geodesic dome. The simplest of these is the tensegrity octohedron. It is formed by three internal

in tensegrity structures:



the tensile forces exist in a network, closed and continuous.

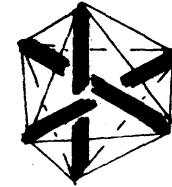


and each strut is stabilized by a minimum of 3 tensile forces at each end.

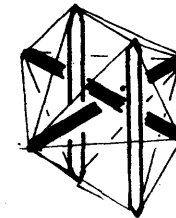
compressive members which are connected by a network of twelve tensile members; these tensile members being the edges of the octohedron. In the platonic octohedron the three struts are orthogonal. They cross at the center of the octohedron, touching but not connected. Formally this crossing defines a corner, i.e. the intersection of three planes. This will have important implications later.

The t-octohedron can be developed in three ways. One way is by 'expanding'. A t-octohedron expands by replacing each compressive member with a pair of struts. This pair is parallel to the strut which has been replaced. The pair is then free to spread apart, remaining parallel, such that the plane they describe remains perpendicular to the other struts. This can be done with one or both of the remaining single struts. When the octohedron is expanded, the internal corner disappears. Instead the struts are skew and only their projections cross. The corner is no longer defined but only a possibility.

the t-octohedron



an octohedron  
once expanded

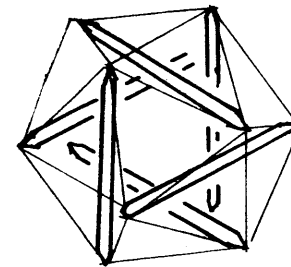
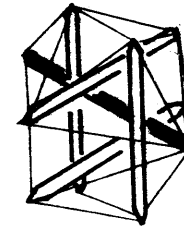




It might be termed a virtual corner. As the octohedron is expanded the number of these virtual corners grow, depending on the number of parallel pairs of struts. With one pair of parallel struts there are three virtual corners, with two pairs there are nine virtual corners, and with three pairs there are nineteen virtual corners. This final form is the t-icosohedron. Like the platonic t-octohedron the platonic t-icosohedron contains struts which are orthogonal. However, these struts do not touch each other. They are totally islanded or discontinuous. Their connection is the network of thirty tensile members which are the edges of the icosohedron.

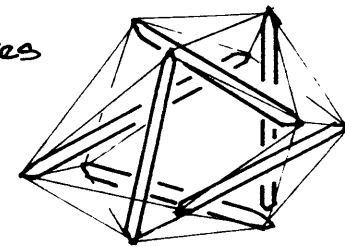
It should be noted that these structures need not be platonic. The struts can be the same length or not, as is the case with the tension members. Tensile members of different lengths will cause the struts to change their relative position or direction. As long as the icosohedron remains

an octohedron  
twice expanded



an octohedron  
3 times expanded  
= an icosohedron

these structures  
need not be  
platonic



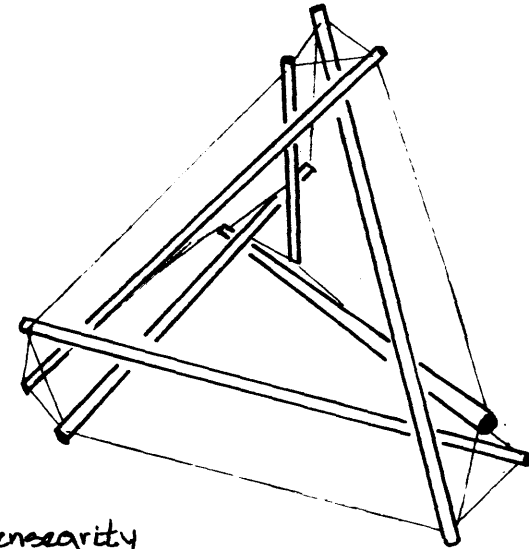
uniformly convex, the structural system will work.

Another development of the t-octohedron is achieved by viewing the crossing of the internal compressive members as the corner of a larger solid where each corner is the terminus of three edges. There are two such solids: the tetrahedron and the cube. The colinear tensile members of adjacent corners in this solid are unified, as are the colinear compressive members, to form the solid.

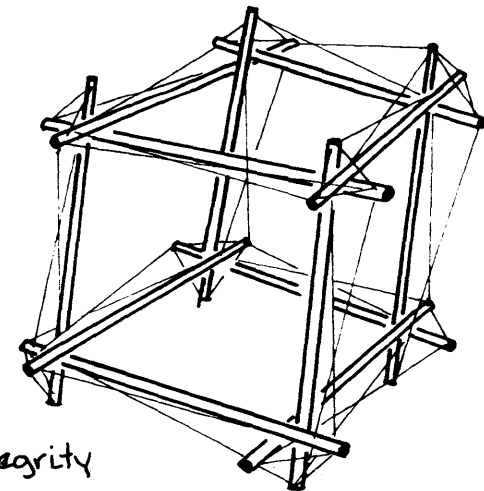
A further development of the t-octohedron leads to the formation of the geodesic dome. Five t-octohedra can be strung into a ring such that two struts of each t-octohedron are united. This ring of struts forms a pentagon. In like manner a triangle can be constructed. These pentagons and triangles can be combined forming the geodesic dome.

#### HISTORY OF TENSEGRITY DESIGN

Buckminster Fuller has, of course, done extensive work with domes. So it is logical that when he

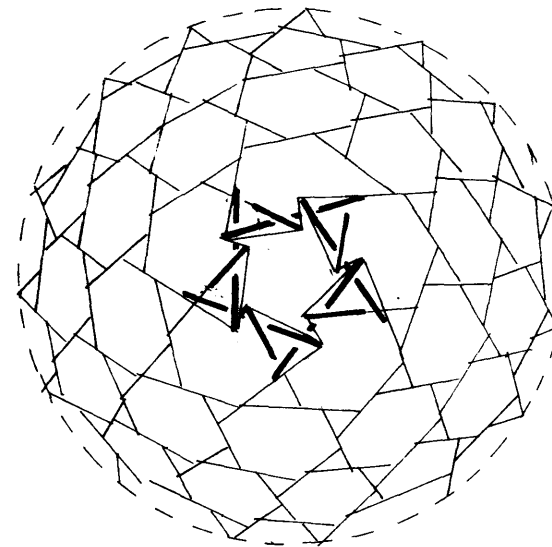
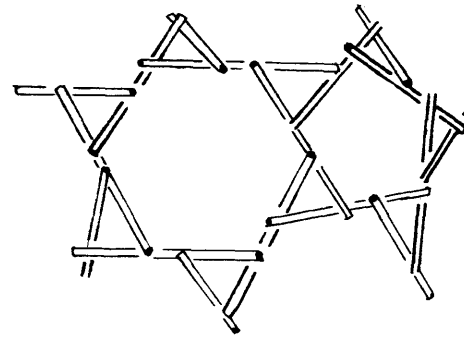


a tensegrity  
tetrahedron



a tensegrity  
cube

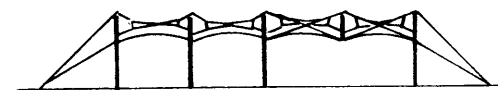
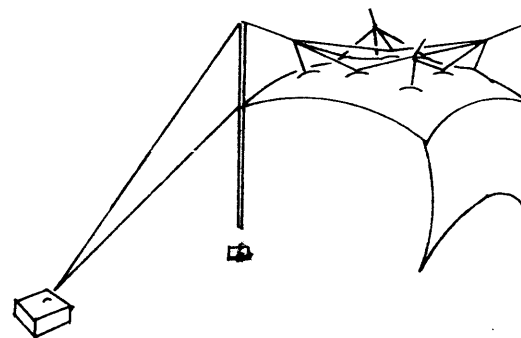
studied tensegrity that he would apply it to his domes. The pattern of connection of the compressive tensegrity struts was compatible to the great circling of the dome struts. The skin replaces the tensile members, and applies no bending moment to the structure, which remains in pure compression. Thus the skin and structure work together synergetically. The two drawbacks to this application are common to many domes. The dome offers few if any clues to its internal partition. It is one big space which is difficult to break up with normal rectilinear walls. In this case the tensegrity network remains in the shell of the dome and is subject to the same problem. The other problem is in the rigidity of the individual panels of building skin. The edge of each panel is in tension as it coincides with the tensile member of the tensegrity. The interior of the panel, however, is not stressed. Particularly with tent-type skins this allows for wrinkles, flutter



a tensegrity dome

and other problems.

The other thrust akin to tensegrity design, the work of Frei Otto, contrasts with the work of Fuller. The components of his tent designs include tensed cables and struts in pure compression, but what Frei Otto uses is not, strictly speaking, a tensegrity system. He has instead applied principles and components of tensegrity into his tent designs. One instance of this is a proposed roof for a site in North Peckham, England. Here we see two applications of tensegrity principles. The first is as a means of providing intermediate points of support for his membrane. To do this he develops a three dimensional network of tensile members. This reduces the number of columns needed to support the membrane. Further, this network begins to enclose the columns until finally the columns take the form of a t-octohedron. By employing the t-octohedron the forces are locally turbined (redirected) toward the base of the column. This reduces the



after NORTH  
PECKHAM design by FREI OTTO.

area encumbered with anchorage lines. But like Fuller's application to the dome, this is again a limited use of the tensegrity principles. The tensegrity structure is utilized as a component of construction; i.e. as a column or a membrane strut.

This study investigates tensegrity principles as they apply to tents. Basic to this is understanding how you might use a tent. One of the strongest features of a tent as a building skin is its ability to be selectively permeable to light, wind, and moisture. Its ability to transmit or reflect light radiation, to ventilate a space or block the wind, to block rain or allow it in, can be mixed in a variety of unusual ways. It should be noted that based on current research, a range of permeabilities to thermal conduction can now be developed for tent skins, permitting the maintenance of a temperature differential of as much as thirty degrees

on a winter day. Tent skins are also being developed which are so tough that they can only be pierced by a diamond edged knife.

Because a tent has limited capabilities to buffer the effects of climate (i.e. temperature, rain, sun, etc.), assumptions must be made about comfortable uses underneath the tent skin. The following chart indicates the different combinations of permeabilities to the elements required by different tent uses.

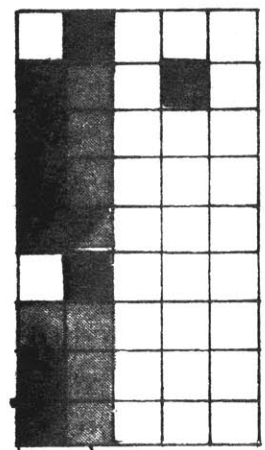
(See chart on page 14)

Porches do not require insulation or containment, only shade from the sun and possibly protection against wind, rain and insects. A tent-like enclosure would keep a porch warm enough for comfort in the fall. In the winter the addition of a tent membrane outside a house will blanket it from the wind. Although it is unrealistic to expect a tent alone to provide enough comfort for sleeping during extremely cold weather, it can provide a thermal barrier to slow

# DESIRED PERMEABILITY OF TENT SKIN TO THE ELEMENTS

great ■  
minor ■  
none □

porch  
greenhouse  
house  
courtyard  
bay window  
awning  
walkway  
camp tent  
skylight



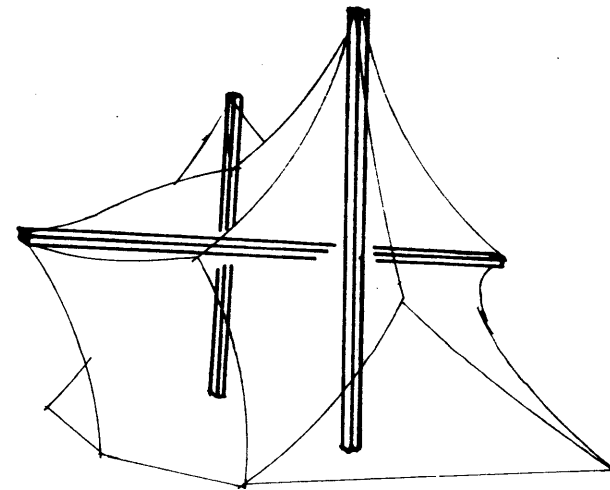
radiation  
wind  
rain  
puncture

down heat loss. This application is similar to Fuller's idea of doming over New York City but could be carried out at the neighborhood or single-dwelling scale.

#### TENT-TEGRITY SYSTEM

This study focuses on a tent building system based on tensegrity principles. Its point of departure is to model the cable network of the t-octohedron and of the t-icosohedron as a double curved surface. The tent skin stabilizes the structure underneath it as in the applications of Fuller and Otto. However, the configuration of the compressive members in a tensegrity tent achieves a unique benefit. The roof comes around to enclose space on all sides. It does this through the action of horizontal compressive members which are restrained by the membrane at both ends.

In the design and construction of the tent skin,

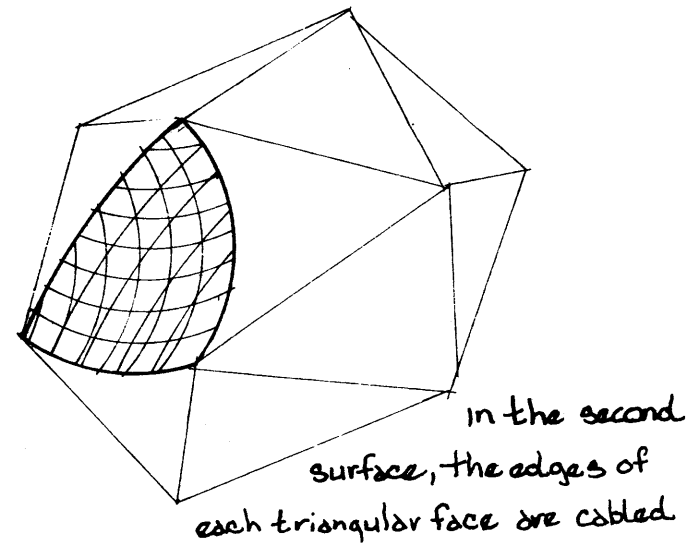
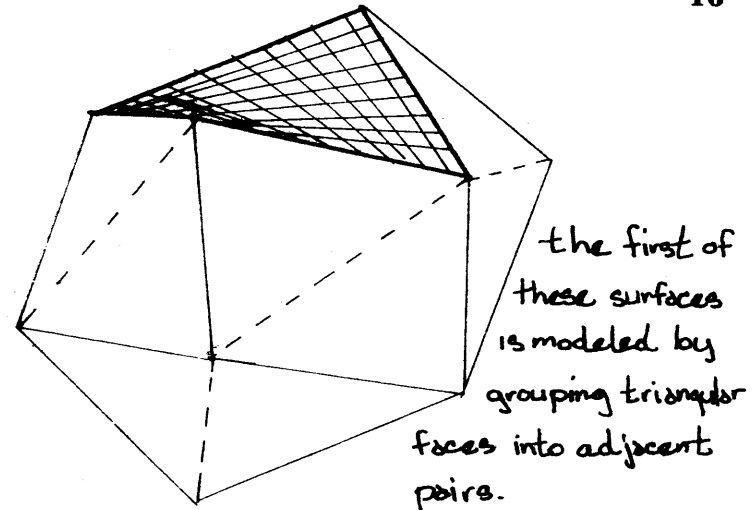


*the point of departure is to model the cable network as a double curved surface.*



there are three patterns in which the membrane can be cut and fitted to form a rigid prestressed surface. The first of these patterns is modeled by grouping the triangular faces into adjacent pairs. If each edge of each triangular face represents a cable, the cable at the common edge of each triangular face can be eliminated. The struts will remain stable as each end is held by the minimum three tensile members. The vertices of each pair of triangles describe the high point, low point, high point, low point relationship like the corners of the hyperbolic paraboloid, a basic anticlastic surface.

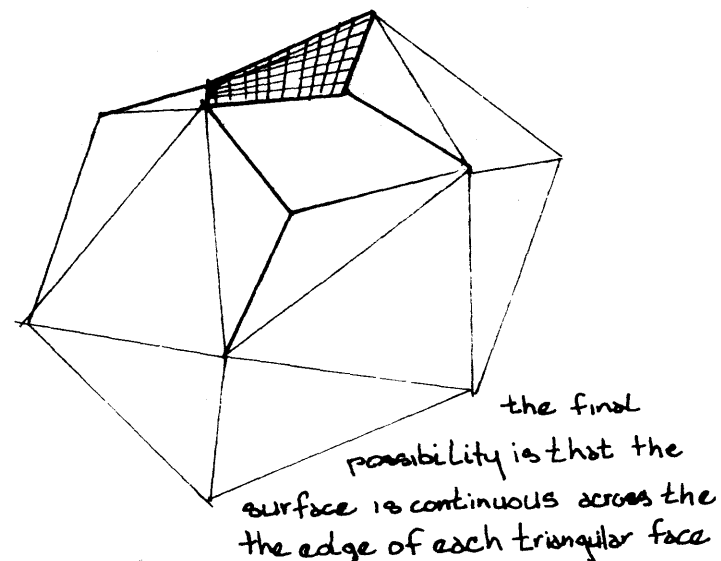
In the second pattern, the edges of each triangle are cabled and describe a ridge or discontinuity in the surface. The triangular faces are bounded not by straight lines, but by curves concave toward the center of the icosohedron (or octohedron). In this case the minimum surface of the triangle is a



section of a sphere where the edges are great circles. The skin is scalloped inward due to the outward force of the struts.

The final possibility is that the surface at the edge of each of the triangular faces is continuous and not a ridge. The surface is anticlastic in this area like a hyperbolic paraboloid. But as the surface approaches the vertex opposite the edge, its curvature inflects. Here it is in the realm of one of the other two edges. Thus each triangular face is composed of three parts; each being part of an anticlastic surface shared with an adjacent triangular face. Any of these three possible patterns can be prestressed for greater rigidity.

Prestressing can be provided by a cable network which also reinforces the membrane. Once installed the cable network defines a modular partition of the tent skin. Some panels may be transparent, others translucent and others empty. At times a



porous membrane is desirable; at other times, a skin which will insulate a space.

The anticlastic surface which subdivides each face of the icosohedron (or octohedron) is the most effectively interrupted. The edges of the individual anticlastic surfaces define a network of cables which can be stretched to provide a framework for individual panels. This configuration is superior for two reasons. Each edge of an anticlastic surface is a straight line. The network of cables can be prestressed such that the cables remain stable if a panel is removed. Unfortunately, this is not the case of the inward scalloped surface. Here the membrane stresses the cables to insure their curvature. When the skin is partitioned, the cables will slacken. The straight line edge of the anticlastic surface offers another benefit. It provides a useful connecting edge to join the tent to another surface if a panel of glass, wood or other planar

material is to be substituted.

In the interior of the tent-segrity the major design determinant is the compressive struts which are used as framing. Aspects of this consideration are wide ranging and include the following questions:

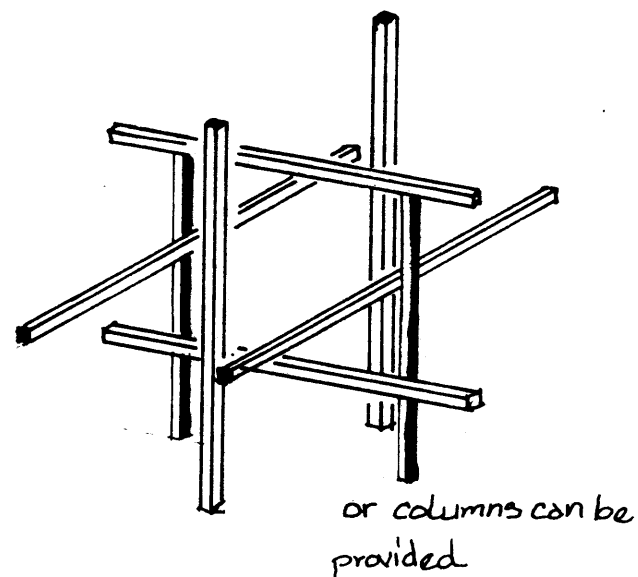
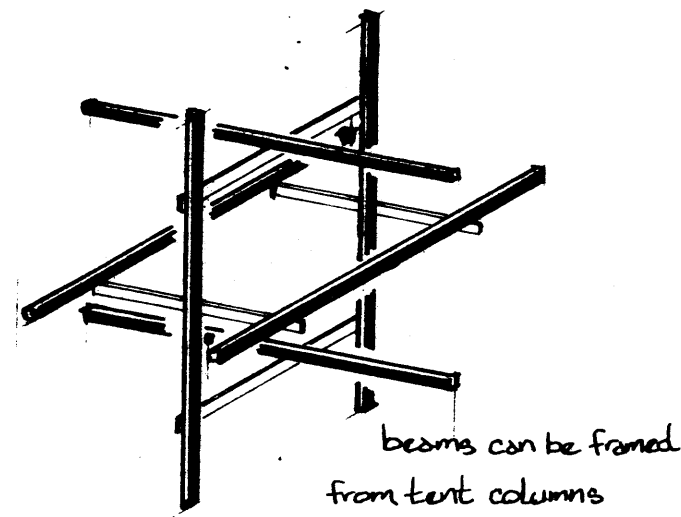
1. Can or must the interior of the tent-segrity solid be partitioned both vertically and horizontally?
2. How can the compressive struts complement the framing of these partitions?
3. What dimensions and proportions must the tent-segrity solid have to be useful?
4. Can parts of the tent-segrity solids stand alone usefully?
5. How can individual tent-segrity solids be combined? How do these combinations effect the useful space of the tent?

The internal framing of the floors acts independently of the tents structural system. Irregular

live loads might develop complex and troublesome deflections, warps, or tensions in the tent skin. The loads of floors and walls are not carried by the tensile members in the tent although it is technically possible. The compressive members still act as beams and columns. Thus the framing does not load the tent and the tent only loads the internal structure in compression. Even so, this method compares favorably with external shells of conventional buildings which: 1) apply moment to the structure and 2) are not tied down against uplift forces of the wind.

Two systems of internal support present themselves. These two systems of support either provide columns at points where the horizontal struts cross, or support each pair of horizontal struts with primary beams from the vertical struts of the tent.

The use of struts as beams and columns assumes tents of a certain scale. This assumption is valid because struts of less than floor to ceiling scale

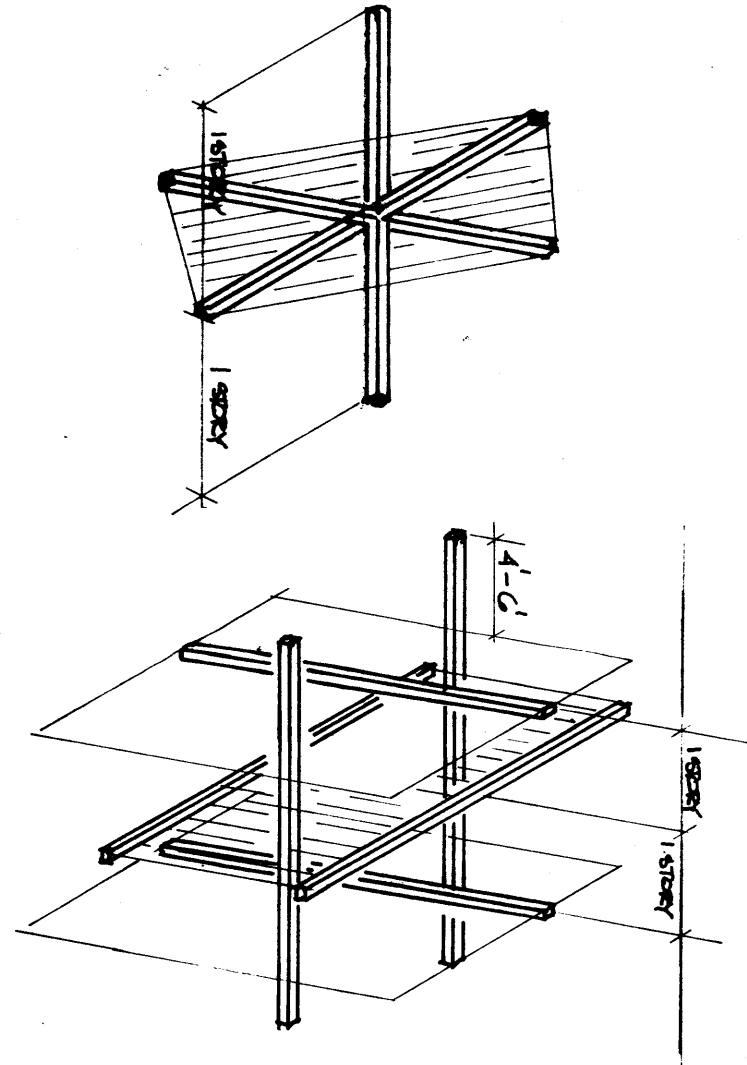


become barriers. Compressive struts are usually continuous between end connections to the tent due to the difficulty of interruption. Each horizontal strut must be at least of head height above the strut which it crosses. The vertical distance between horizontal struts therefore tends to be from six to eight feet. The t-octohedron becomes at least twelve to sixteen feet tall. However, the t-icosahedron need not be equally proportioned. The vertical struts need not extend to head height beyond the last strut. If columns extend four feet above and four feet below the top and bottom horizontal strut, the structure becomes a minimum of twenty to twenty-four feet tall.

The horizontal proportions are free to change independently. Here the main concern is probably structural framing. The limits are the span between beams and the density of columns.

#### APPLICATION

A wide range of concerns have emerged in the



application of this system. The t-octohedron is a module which as an individual entity is like the dome, a difficult building to use. But the rectilinear frame of this structure provides a means of dividing or combining modules into a more useful form.

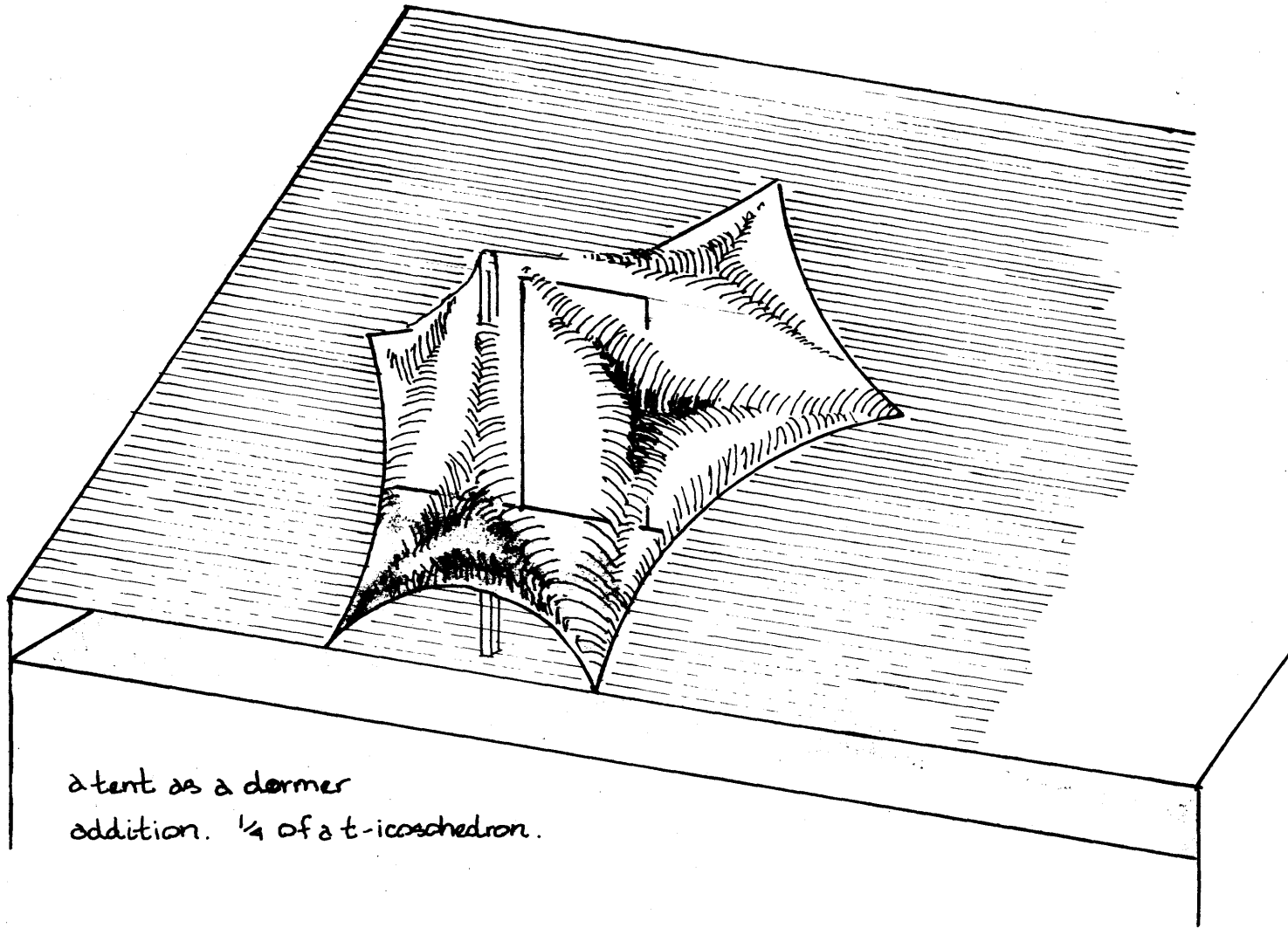
The ability to expand the octohedron or contract the icosohedron provides another helpful variation of form. The icosohedron as the expanded form provides the greatest spatial definition with its six struts and nineteen virtual corners whereas the octohedron defines a basic unit of form, a single corner with three struts. Each of these different variations of the basic tensegrity forms are effective at specific scales of construction.

For small scale uses only a part of either the t-octohedron or the t-icosohedron allows unencumbered space.

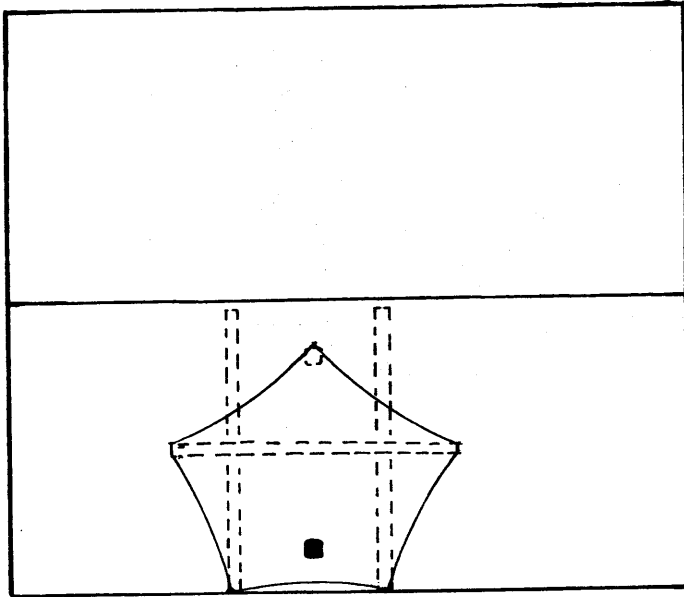
Using the t-octohedron module completely defines

at least a two story space, and the t-icosohedron defines a three story space. Thus their combinations become quite large. The examples which follow show this range of application.

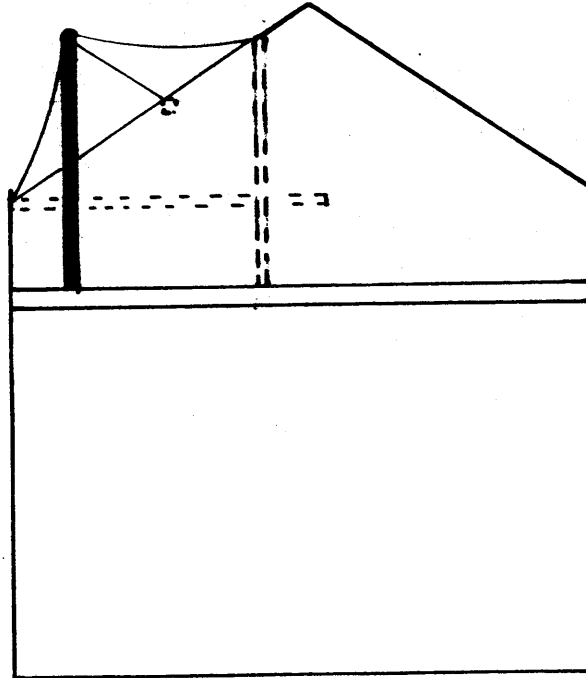




a tent as a domer  
addition.  $\frac{1}{4}$  of a t-icosahedron.



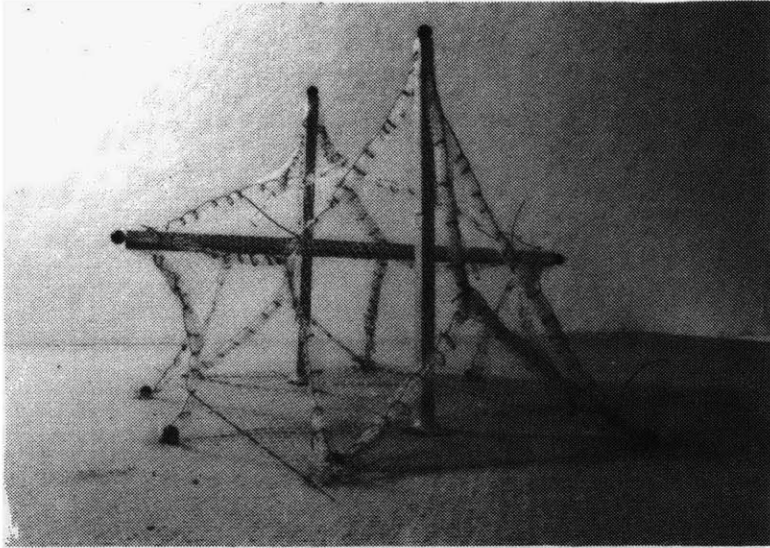
ROOF PLAN  $\frac{1}{8}''=1'-0''$



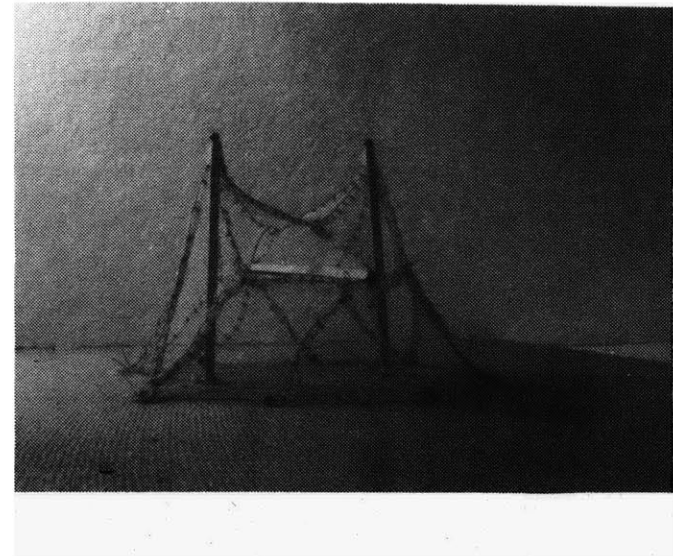
SECTION  $\frac{1}{8}''=1'-0''$

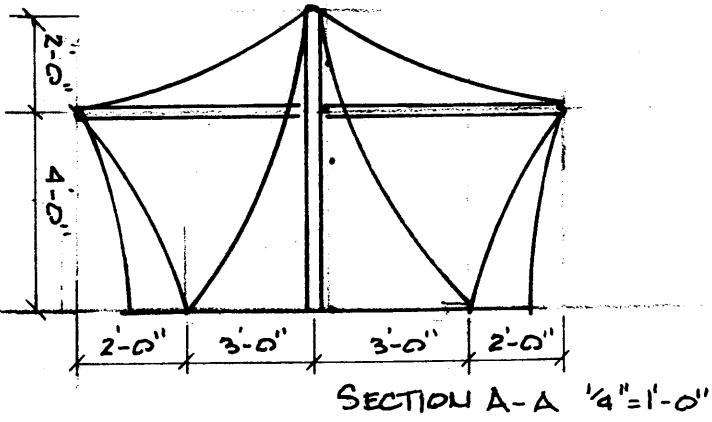
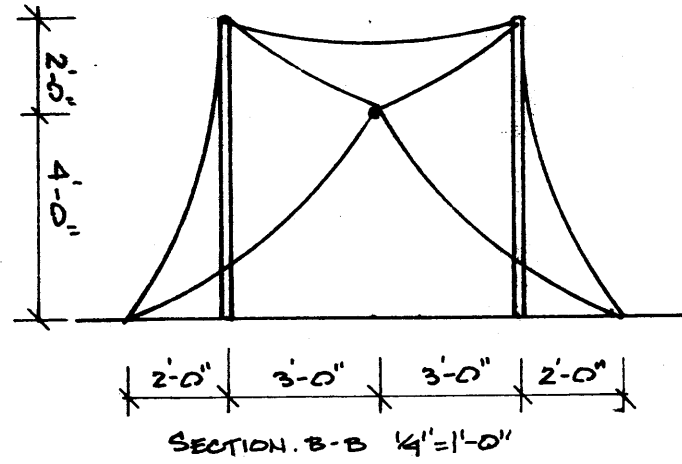
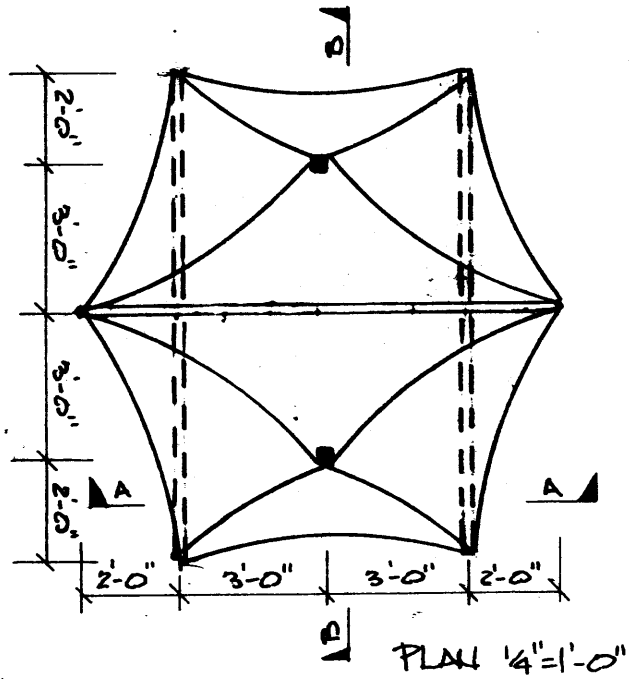
the tensegrity structure save one column is virtual. the form is maintained by the roof.

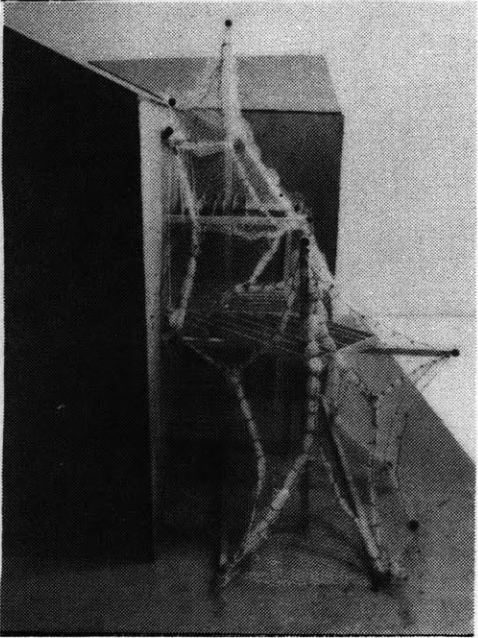
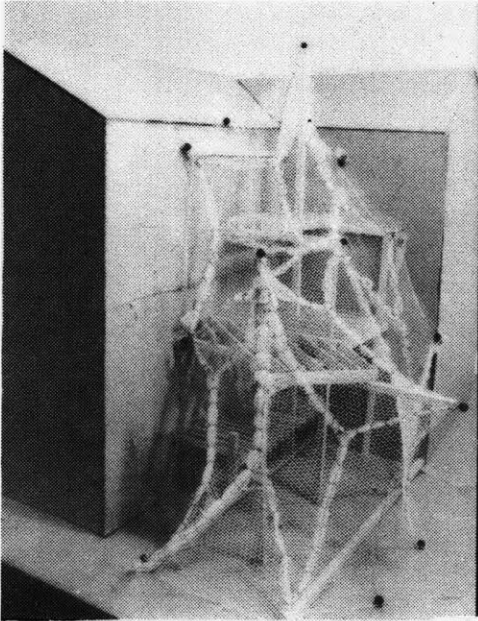
to construct: apply to roof, seal joint, cut roof from underneath, and prop up tent with pole.



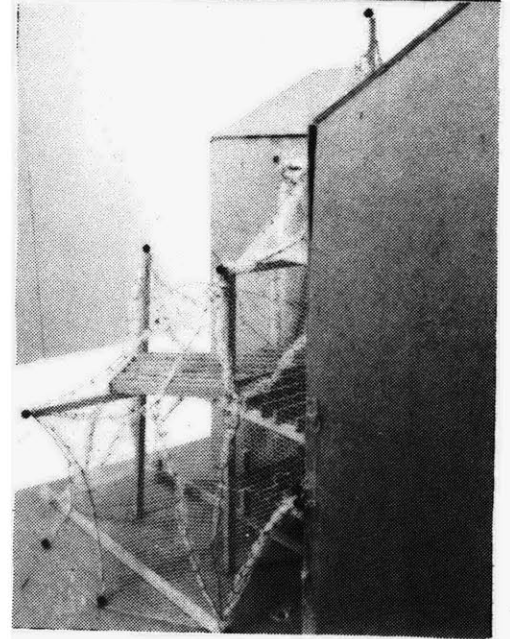
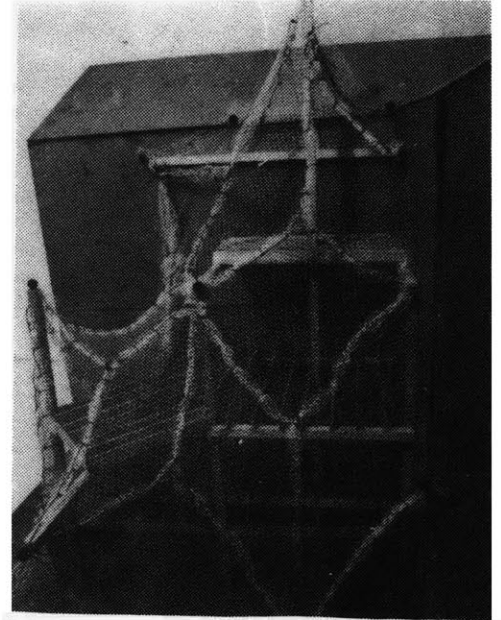
à tensegrity camping tent.  
1/2 of a t-icosahedron.

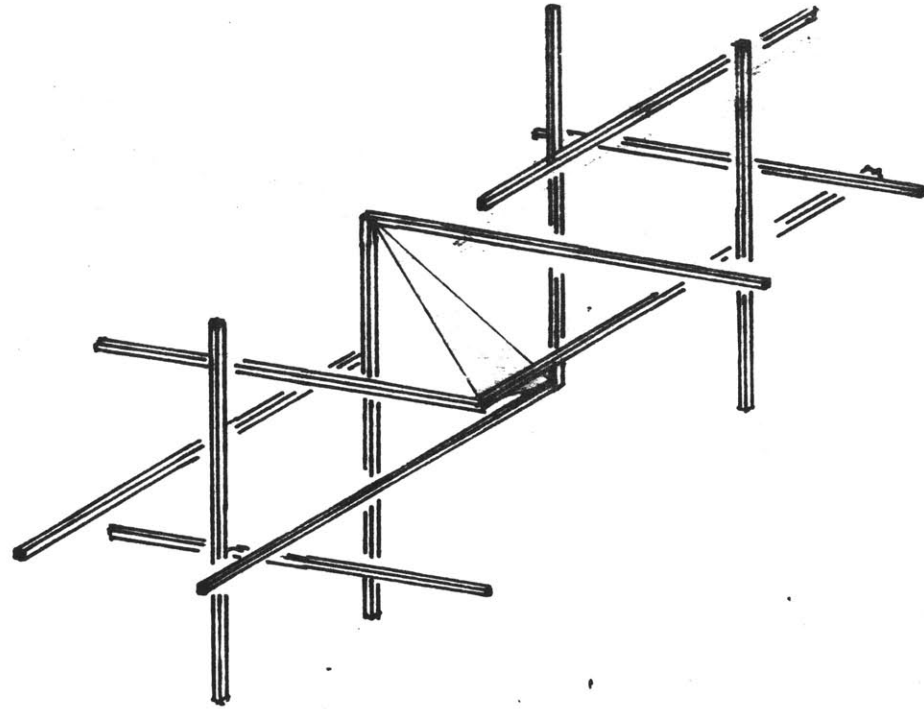
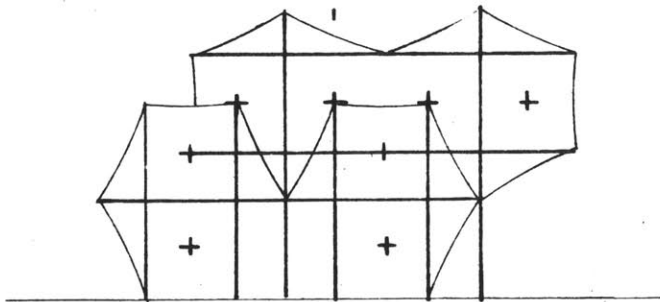
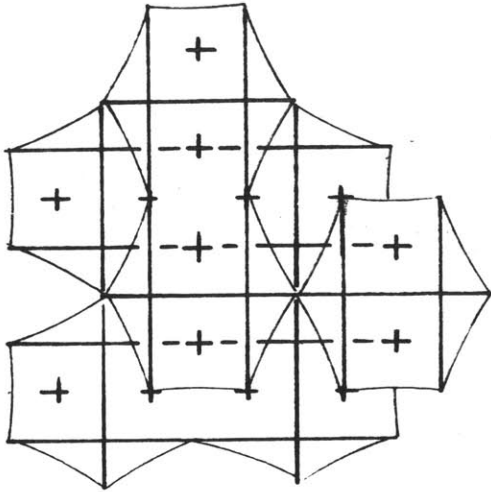




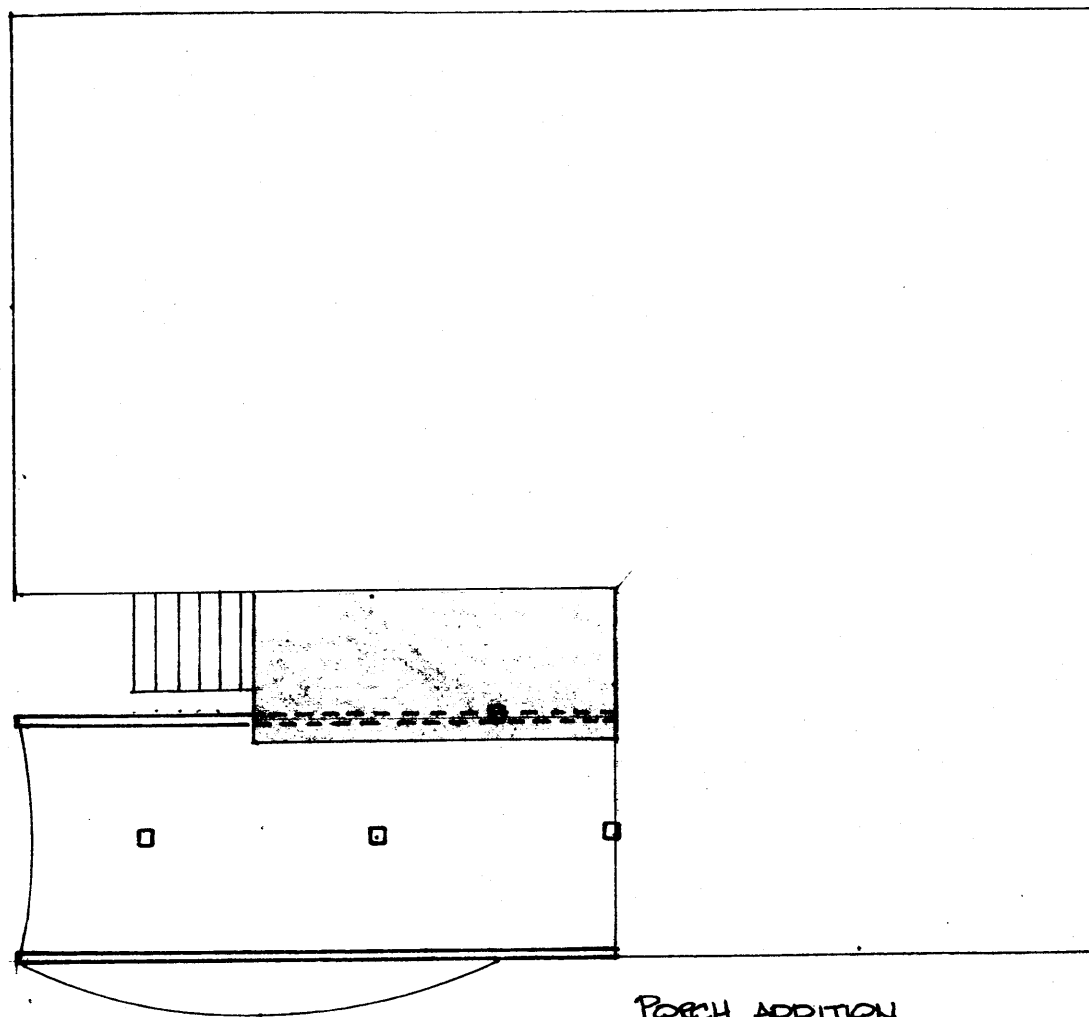


house porch addition  
based on 'tight' packing of  
t-icosahedra.



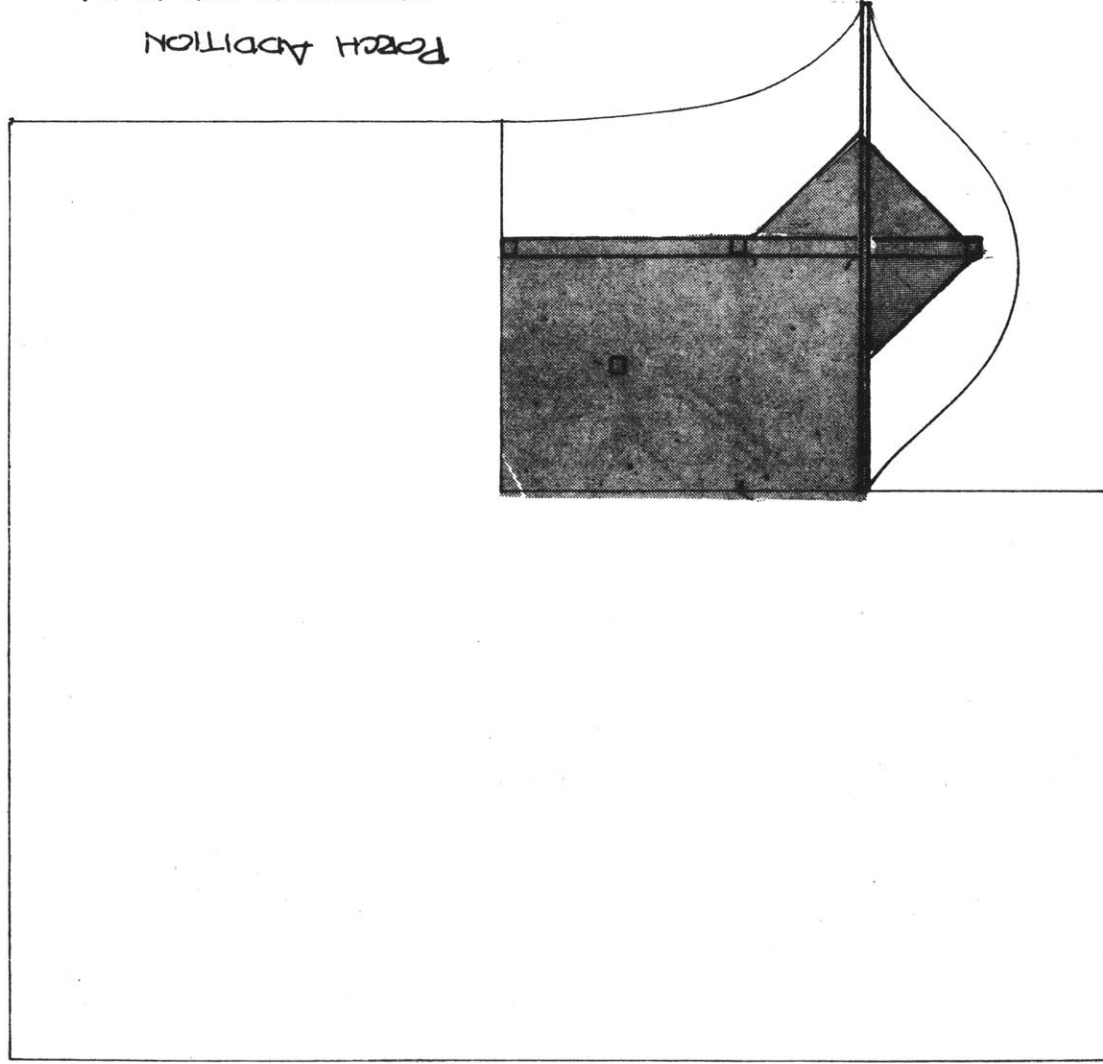


'tight' packing of t-icosahedra

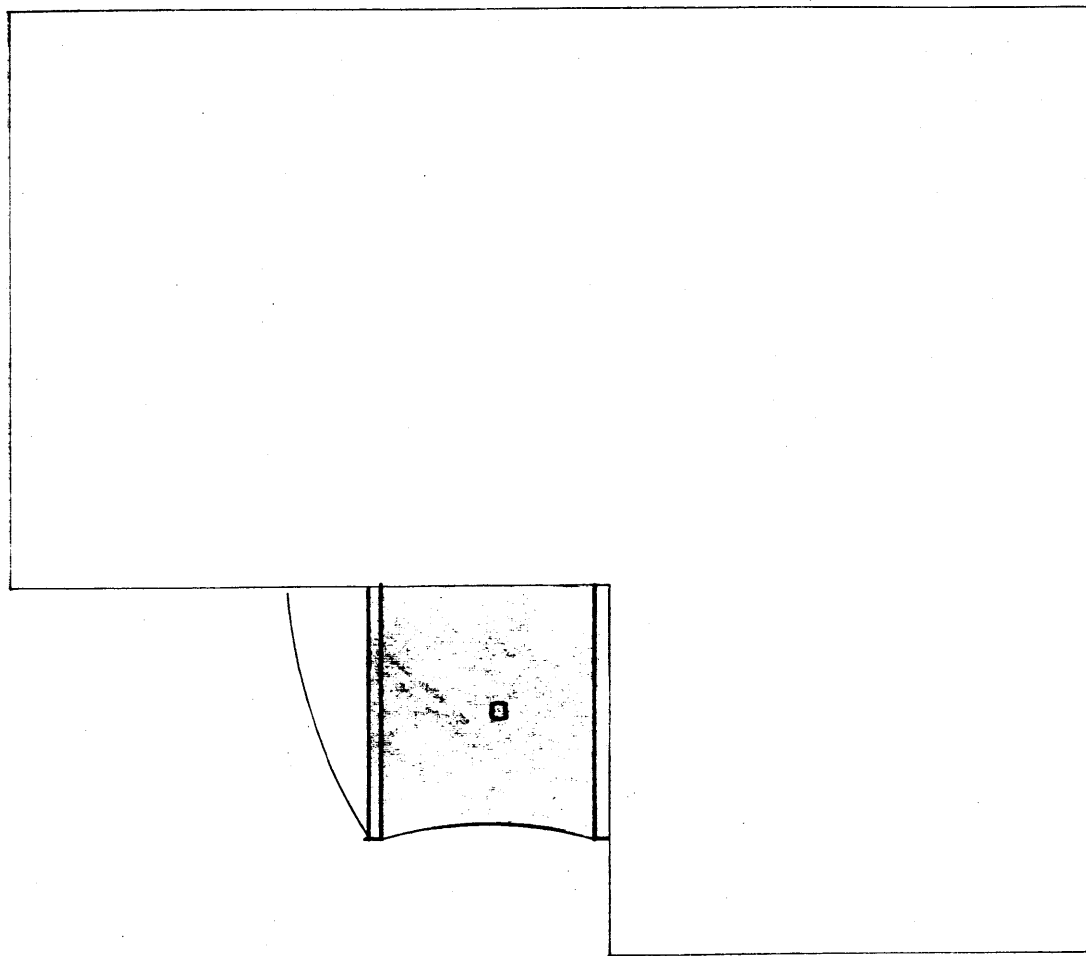


PORCH ADDITION  
GROUND FLOOR PLAN  
SCALE: 1/8"=1'-0"

PORCH ADDITION  
SECOND FLOOR PLAN  
1/8"=1'-0"





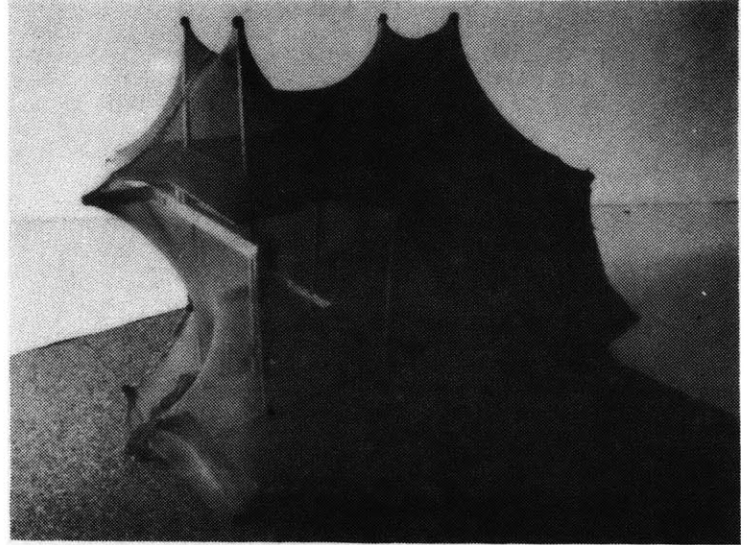


ROOF DECK

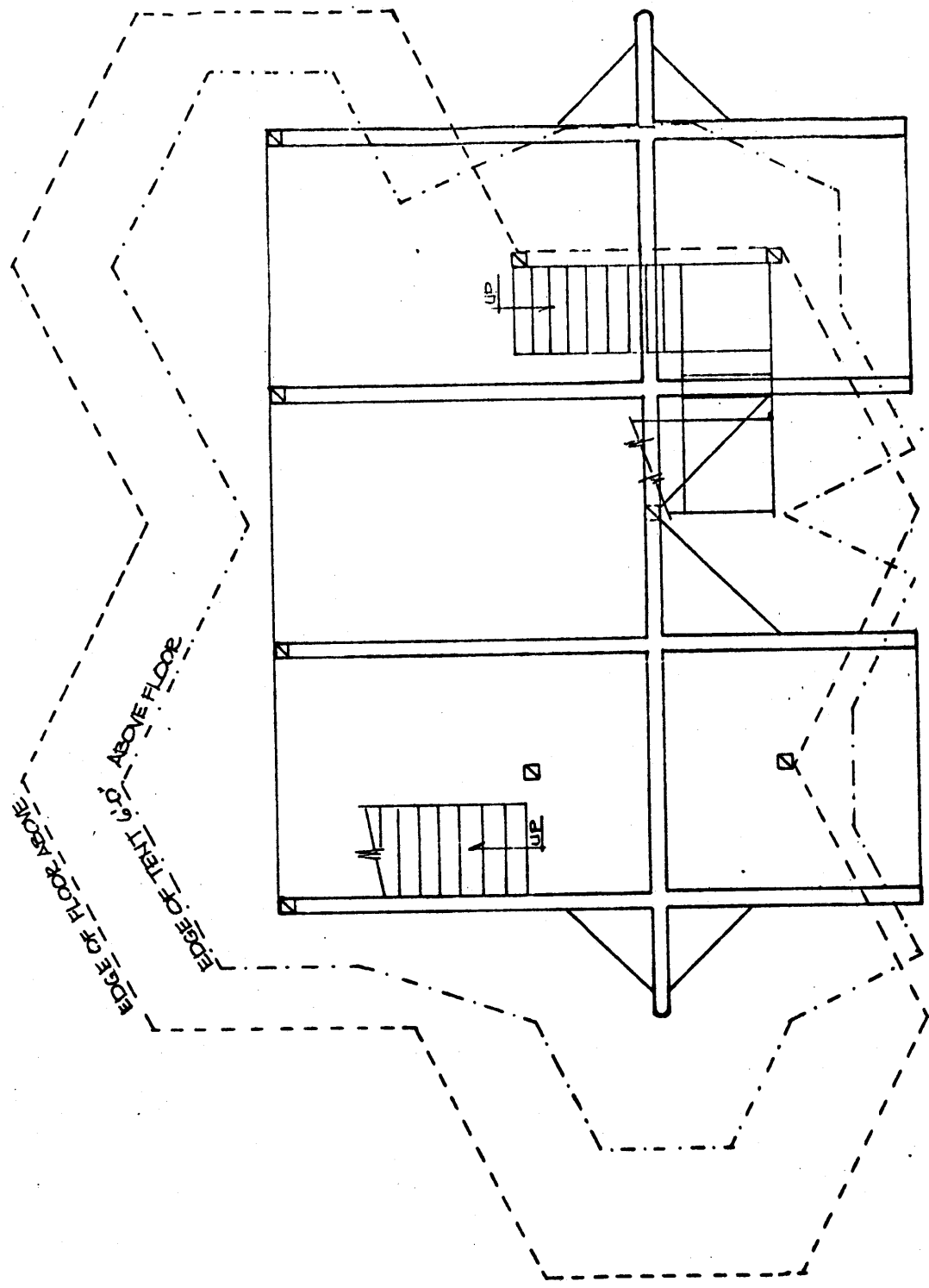
PORCH ADDITION

THIRD FLOOR PLAN

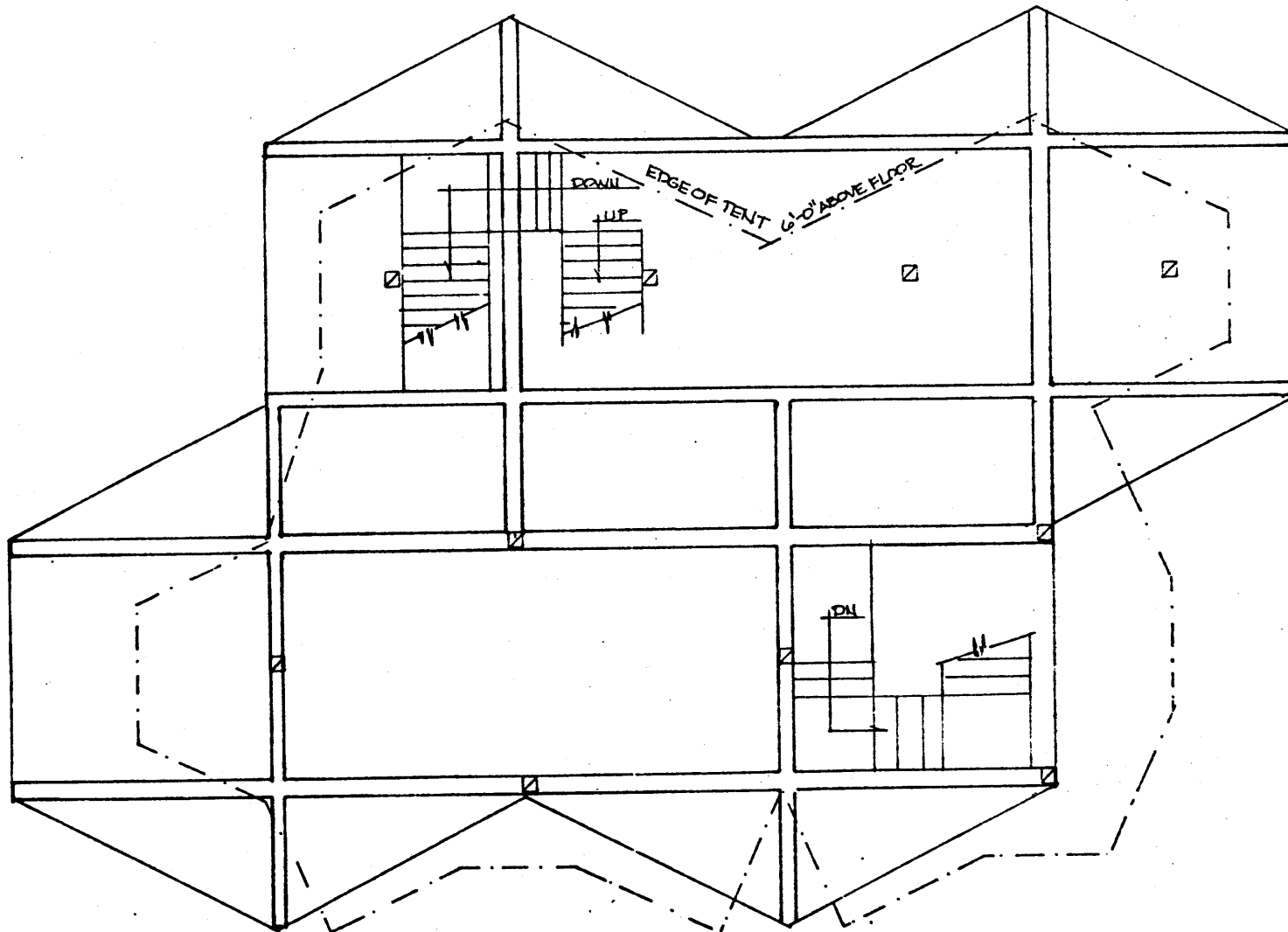
1/8" = 1'-0"



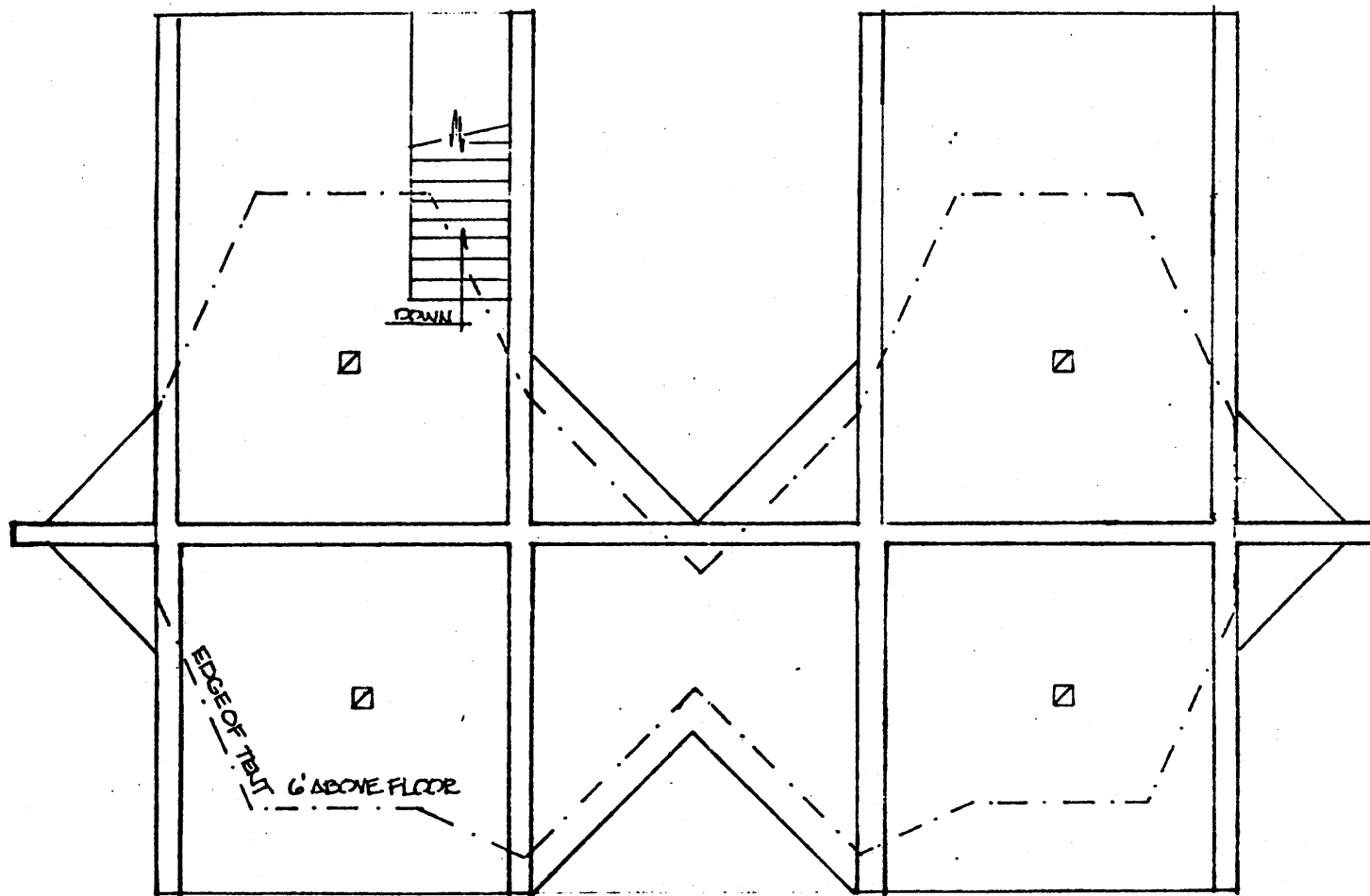
HOUSE - based on tight packing of 2-expanded and 1-expanded octahedra.



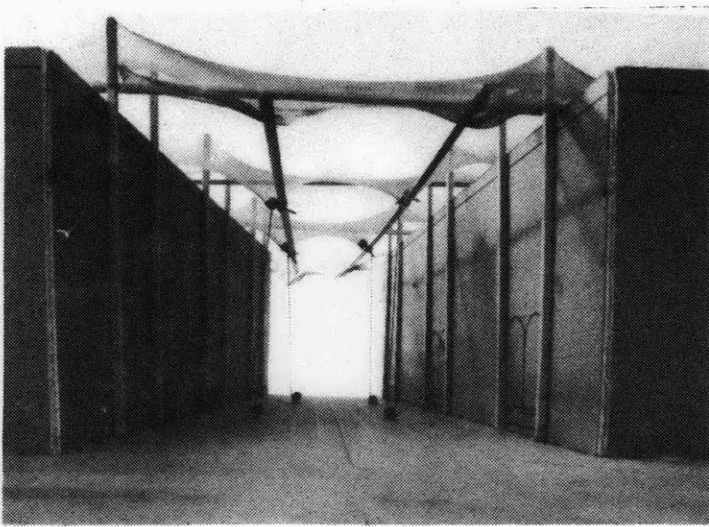
GROUND FLOOR  
1/8" = 1'-0"



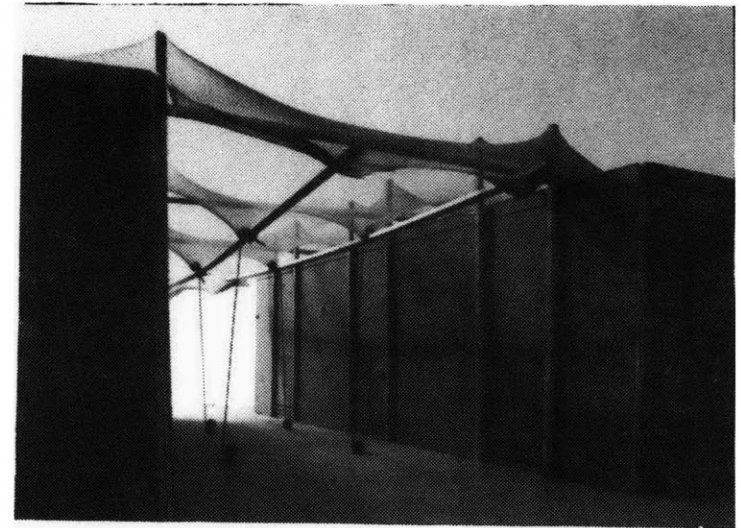
SECOND FLOOR  
1/8" = 1'-0"

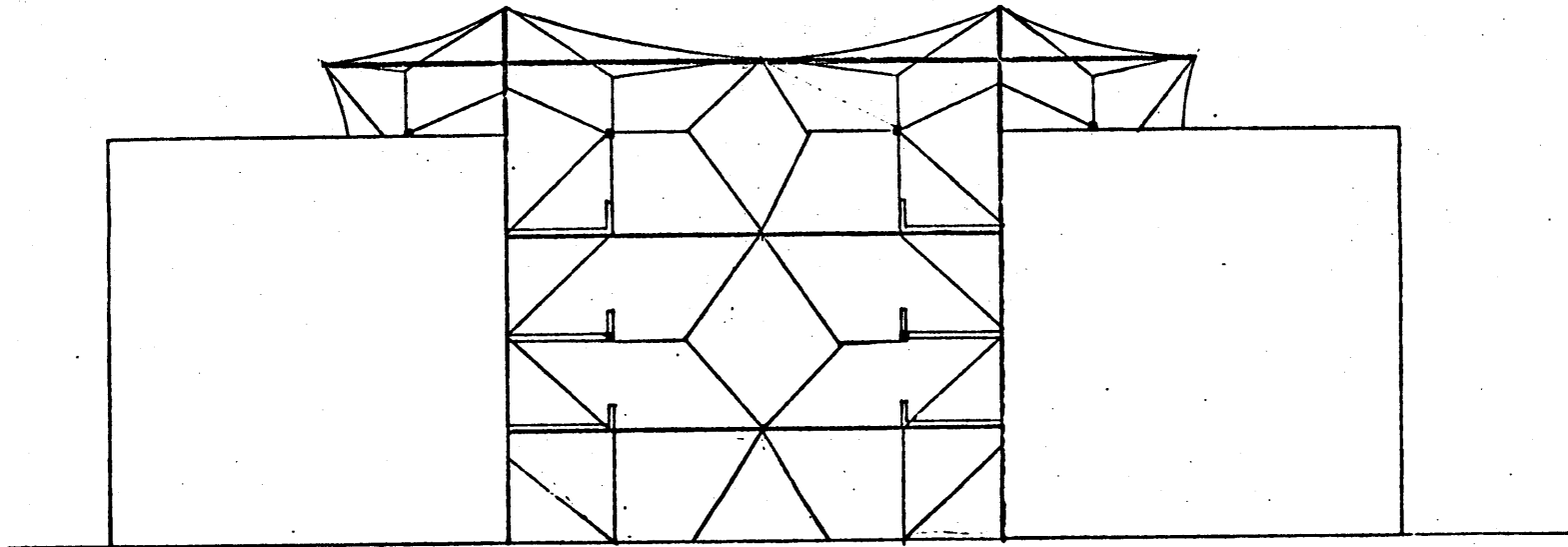


THIRD FLOOR  
1/8" = 1'-0"



tent to cover courtyard between  
rowhouses  
based on loose packing of  
t-icosahedra. (see following page.)

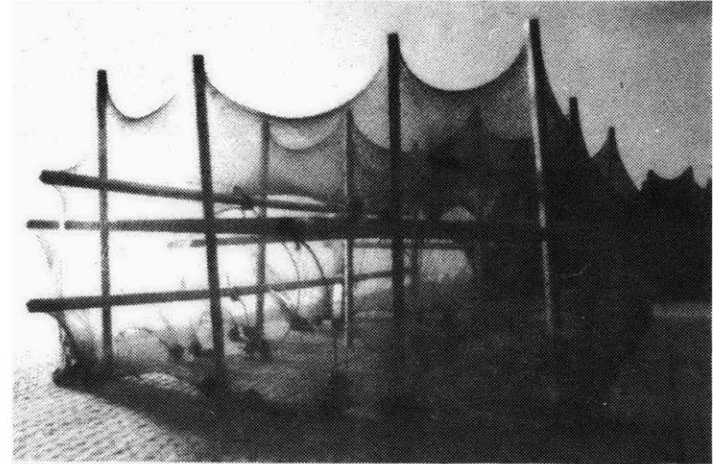
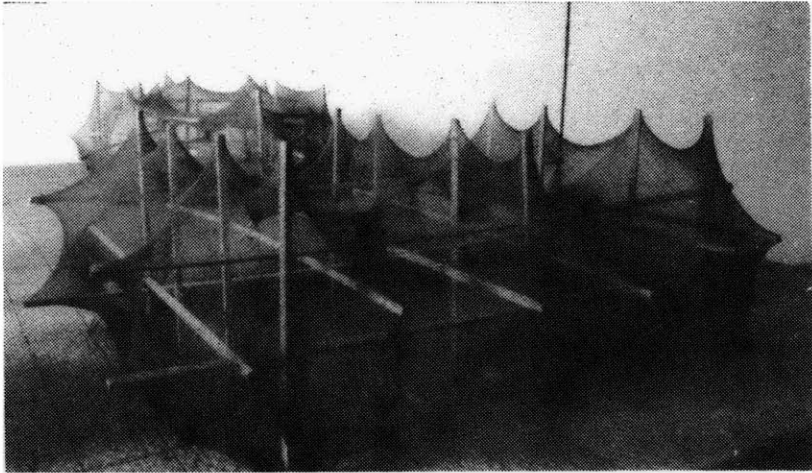




REAR ELEVATION  
OF ROWHOUSE

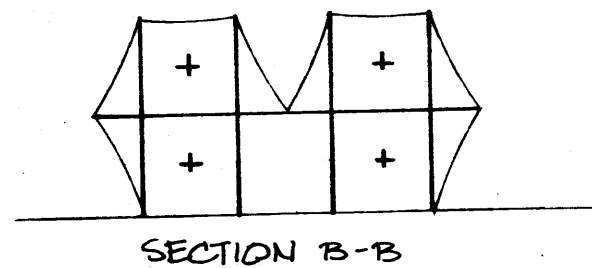
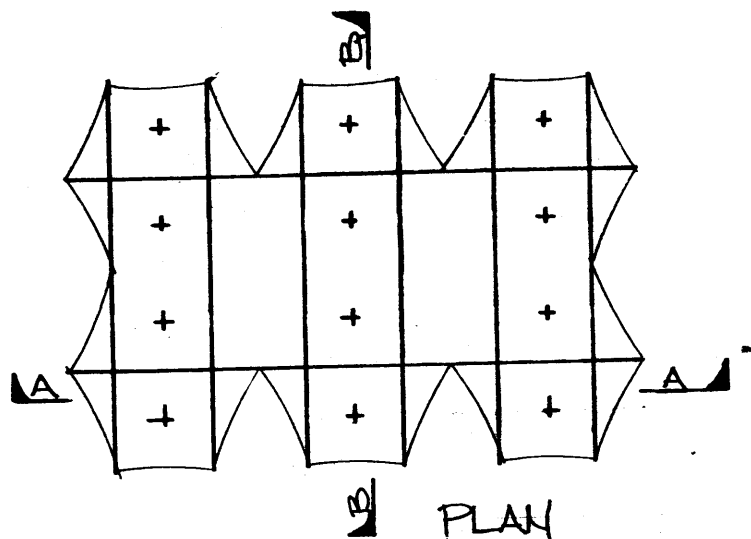
COURTYARD

1/4" = 1'-0"

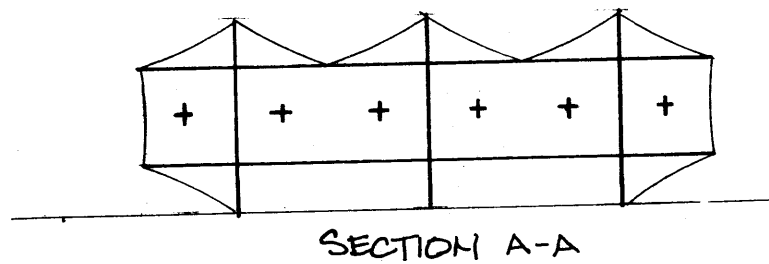


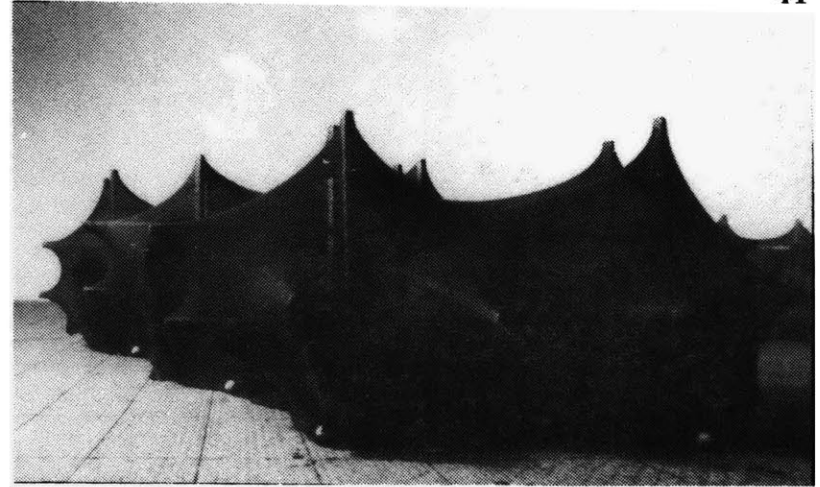
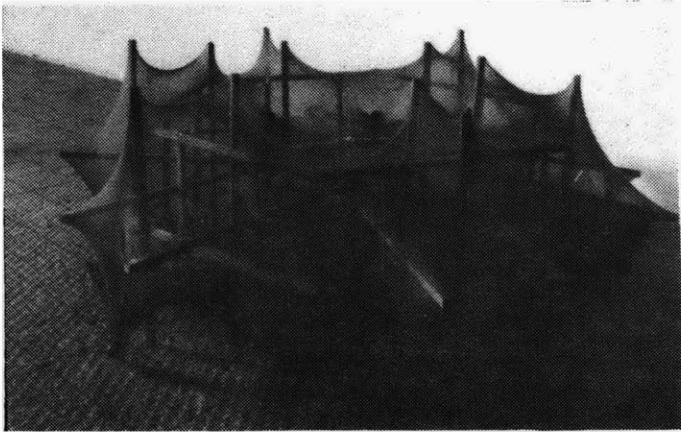
basic loose pack of t-icoshedra



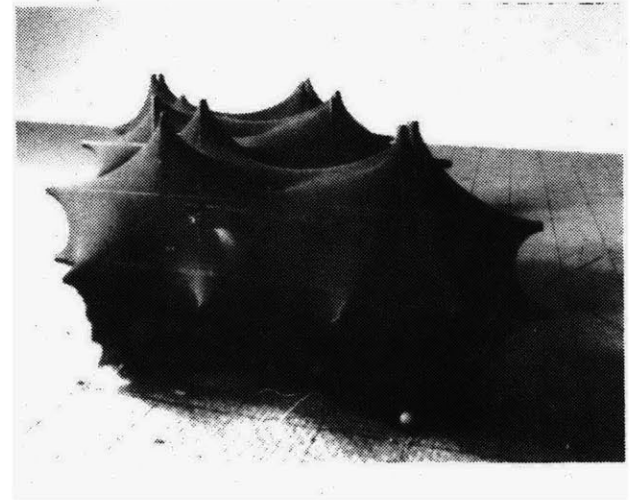


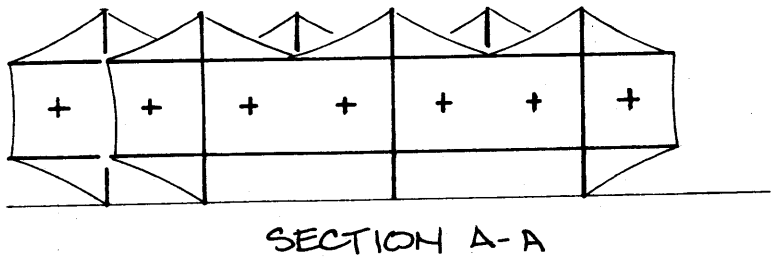
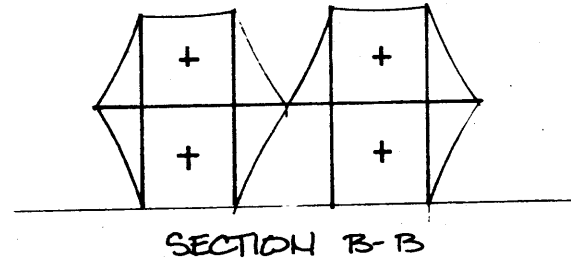
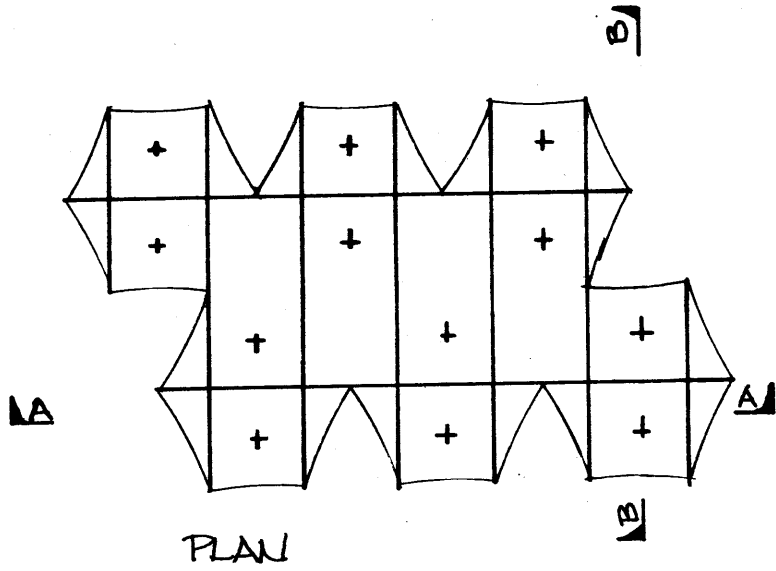
BASIC LOOSE PACKING OF  
T-ICOSAHEDRA.

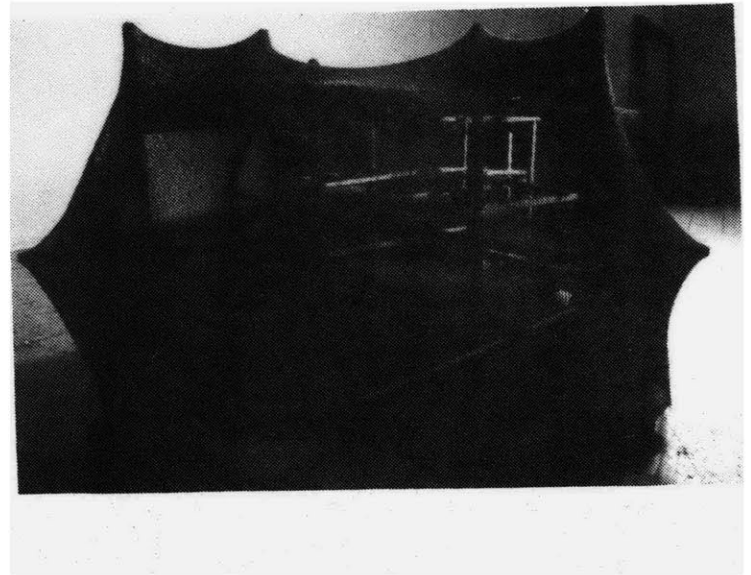
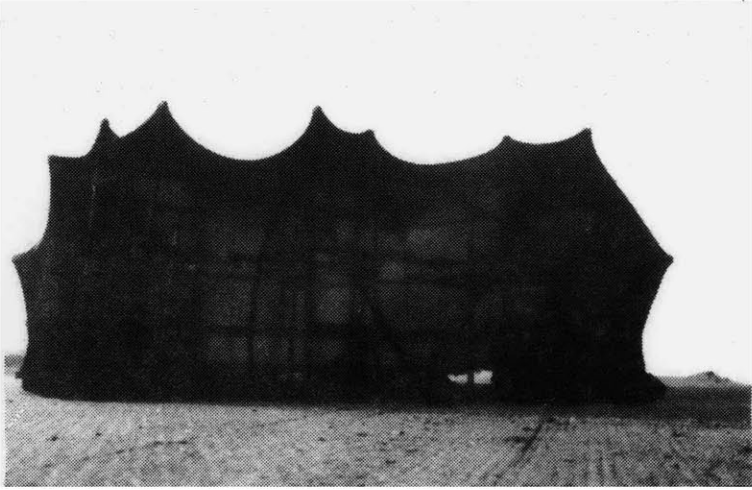


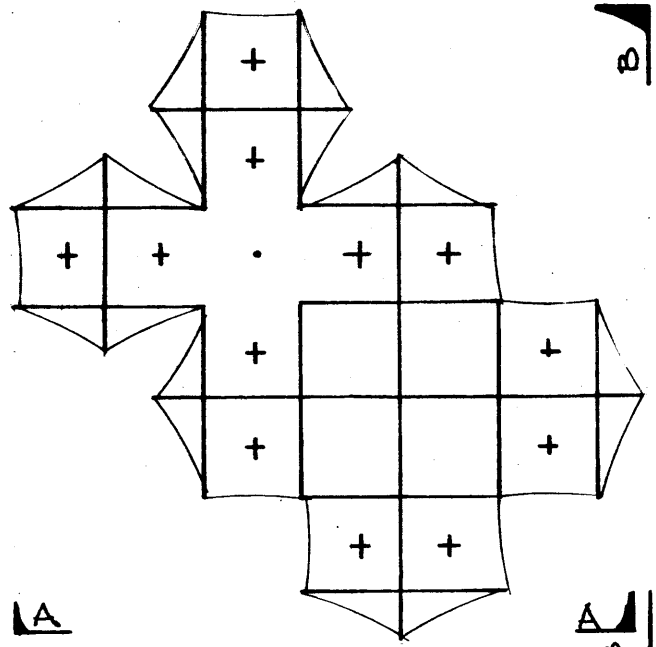


other loose packings  
of t-icosahedra

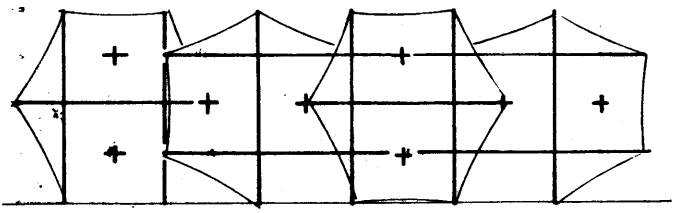




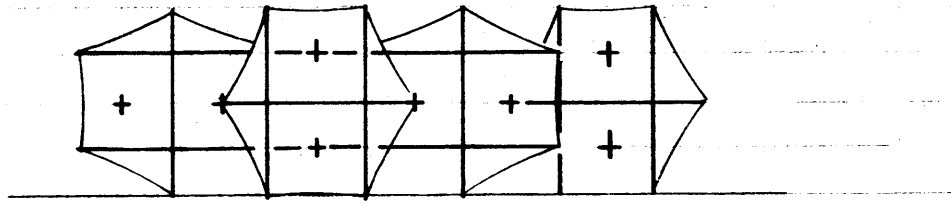




PLAN



SECTION A-A



SECTION B-B

## CONCLUSION

Tent skins are an adaptable building material. Key to this characteristic is their range of permeabilities to the elements.

More usable tent forms can be developed following tensegrity principles. These forms enclose space and offer strong design clues as to the partitioning of the interior space. In addition, they more efficiently use space because they do not require anchorage lines and foundations.

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