Two-Dimensional Deployable Truss Structures for Space Applications

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Two types of two-dimensional deployable truss structures are introduced: 1) a variable-length diagonal member (VLD) truss that can be folded by elongation for some members and 2) a sliding-hinge double-fold (SHDF) truss that can be folded by sliding some hinge assemblies. These concepts are compared to existing concepts of folding by the elongation of some members (Vought double fold or VDF) or by sliding some hinge assemblies (Vought biaxial double fold or BADF). The number of mechanisms to be actuated and locked at the deployment of VLD and SHDF is approximately half that of VDF and BADF, respectively. The packaging efficiency of the newly introduced truss is almost the same as that of BADF and is superior to VDF in the case of the basic configuration. Necessary conditions for the trusses to be folded/deployed are formulated and the design flexibility of each concept in forming a globally curved surface is investigated. VDF and VLD are shown to have relatively large flexibility, while SHDF has the least flexibility of the four concepts. However, a numerical example demonstrates that SHDF still has sufficient design flexibility to form a parabolic surface of acceptable accuracy. Functional models of the new concepts are fabricated for trial and deploy/retract tests demonstrate the practicality of the concepts.

I. Introduction

IN space, it is sometimes necessary to construct structures that are larger than the capacity of the transport vehicle from Earth to orbit. It is then necessary to build the structures in orbit by combining the components of the structures. For cost reasons, it is important to develop techniques of constructing large structures in space that minimize in-orbit activities. Also, it is expected that in many cases the volume of the structural components, rather than their weight, will dominate the transportation cost; thus, it is very important to develop techniques of packaging the structural components very compactly.

To accommodate these two requirements, structures packaged in a very compact volume while being transported and capable of automatic deployment to final configurations in orbit have been proposed and, to some extent, developed. Because of their relatively high rigidity, many one- and two-dimensional truss structures have been proposed as deployable structures.[1-12]

Because each deployable truss has its own advantages and disadvantages, the choice of the most suitable truss is application dependent. Therefore, it is important to develop, investigate, and evaluate as many kinds of deployable trusses as possible. In this paper, two kinds of two-dimensional deployable truss structures are proposed, investigated, and demonstrated.

II. Basic Concepts

Variable-Length Diagonal Member Truss

Figure 1 shows a fully deployed module forming a basic (i.e., regular and flat) configuration of a current two-dimensional deployable truss, called the variable-length diagonal (VLD) member truss. As shown in the figure, the module in the deployed condition is composed of eight rigid face members placed along the edges of the front and back faces of an imaginary rectangular parallelepiped, four rigid cross members placed along the other edges of the parallelepiped, two pairs of flexible face diagonal members extending along the diagonal lines in the front and back faces of the parallelpiped, four rigid variable-length side diagonal members in the side faces of the parallelepiped with internal actuators for extension/contraction, and eight hinge assemblies fixed to each end of the cross members. Except for the cross members, each rigid member is pivotally connected to the hinge assemblies at both ends.

The side diagonal members shown in Fig. 1 are in the contracted state. When they are elongated, the module collapses as shown in Fig. 2. Finally, all members become virtually parallel, resulting in an extremely compact packed state. Conversely, it is redeployed by the contraction of the side diagonal members.

It can be seen that a platform made from this sort of module and arranged in rows and columns sharing a side face of the imaginary parallelepiped (and corresponding members and hinge assemblies), as shown in Fig. 3, can also be collapsed into a compact volume and redeployed in the same manner as shown above.

Many of the previously proposed deployable trusses are collapsed by folding the articulated members. The presence of hinges in articulated members almost inevitably decreases the Euler buckling strength of the members, because of misalignment and reduced bending rigidity at the center hinges, even in

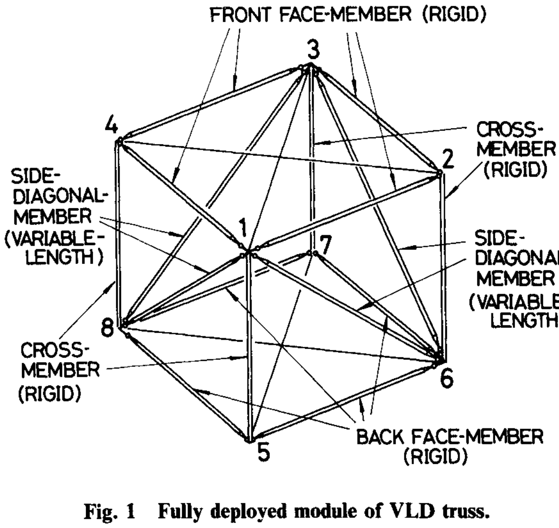

Fig. 1 Fully deployed module of VLD truss.

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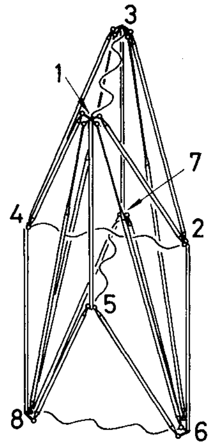

Fig. 2 Half collapsed/deployed module of VLD truss.

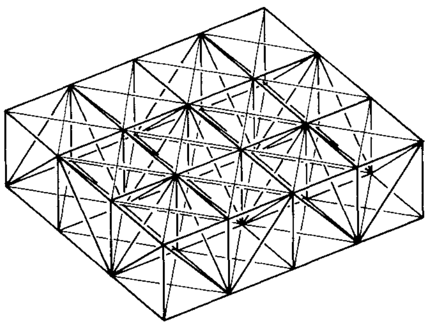

Fig. 3 VLD platform made of a plurality of modules.

the locked state after the deployment. An important feature of this deployable truss is that folding involves only the elongation of members and no articulation. The elongation/contraction and lock mechanisms can be installed at the end of the members so that the Euler buckling strength is not substantially decreased.

To the author's knowledge, Vought double fold (VDF)[1] is the most widely known deployable truss that can be two-dimensionally folded by the elongation of some members. Therefore, in this paper, the VLD truss is discussed primarily in comparison with the VDF.

Sliding-Hinge Double-Fold Truss

Figure 4 shows a module forming a basic configuration of another two-dimensional deployable truss, called sliding-hinge double-fold (SHDF) truss in this paper. The module is the same as that of VLD except that two sliding-hinge assemblies are installed on two cross members instead of the elongation mechanisms of the side diagonal members and that an end of each side diagonal member is connected not to the fixed-hinge assembly mounted on the end of cross member, but to the sliding-hinge assembly.

When the truss is fully deployed, the sliding-hinge assemblies are held against the fixed-hinge assemblies as shown in Fig. 4. When the sliding-hinge assemblies are slid away from the fixed-hinge assemblies against which they are held, the module collapses as shown in Fig. 5 and, finally, compactly packed in the same manner as VLD. It is obvious that a truss platform made of a plurality of the above-mentioned modules in the same manner as VLD can also be folded into a compact volume as well as redeployed.

This truss has the same advantage as VDF and VLD trusses because it has no articulated members and can be folded/deployed by sliding some hinge assemblies. A version of Vought biaxial double-fold (BADF) truss[1] is the only one that has the above advantage and can be folded/deployed by sliding the

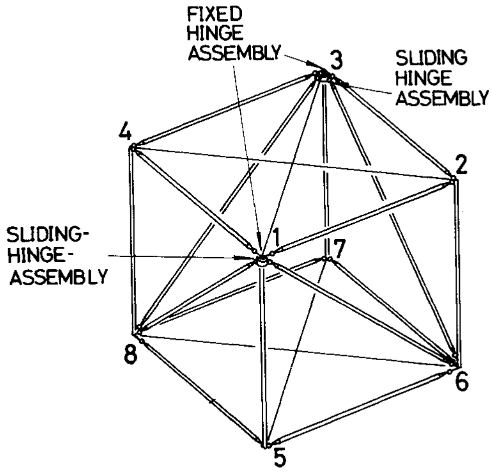

Fig. 4 Fully deployed module of SHDF truss.

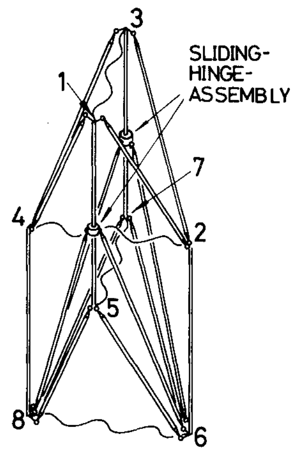

Fig. 5 Half collapsed/deployed module of SHDF truss.

hinge assemblies. Therefore, in this paper, the SHDF truss is compared primarily with the BADF.

III. Number of Mechanisms

Reduction in the number of the mechanisms to be actuated at deployment and to be locked in the deployed state is an important matter for deployable truss structures, because large numbers of such mechanisms not only increase the total weight but also decrease the reliability of deployment.

The module of VDF truss shown in Fig. 6 is different from the VLD in that it has an elongatable diagonal member in both the front and back faces of the imaginary parallelepiped instead of a pair of flexible diagonal members and in that the diagonal members in two side faces are placed along the other diagonal lines. A module of VDF truss has six members to be elongated at the fold. Since four of them are shared by two modules when they are assembled into a platform, approximately four members per module need to be elongated in order to fold a platform. A module of the BADF is, as shown in Fig. 7, similar to that of SHDF in a deployed state, but differs in that all hinge assemblies not connected to any side diagonal members are slidable. In the case of BADF, approximately one hinge assembly per module needs to be actuated because a module has four sliding-hinge assemblies, each of which is shared by four modules.

On the other hand, a module of the present VLD truss has four members that are to be elongated to fold the truss. Since each of them is shared by two modules when assembled into a platform, approximately two (i.e., half those of VDF) members per module are required for extension. A module of the present SHDF truss has two slidable hinges, which are shared by four modules. Therefore, approximately only one-half (i.e., half that of BADF) hinge assembly per module need to be actuated. This extremely low number of mechanisms is the most distinguishing advantage of the SHDF truss. The SHDF truss can be regarded as a derivative of the VLD, where the elongation of four side diagonal members has been replaced by a sliding-hinge assembly, resulting in very few mechanisms.

IV. Packaging Efficiency

Packaging efficiency, i.e., the ratio of the volume of the deployed structure to that of the folded one, is an essential performance index of a deployable structure. For the sake of simplicity, in the following investigation of packaging efficiency, it is assumed that all truss members are tubes having a diameter of d and all modules are cubes of edge length l. It is also assumed that the central axes of all the members connected to a node coincide exactly with the nodal point in the deployed state.

Based on the above assumption, the most compactly folded side faces are as shown in Fig. 8. As can be seen, certain offsets of the hinges from the nodal points are inevitable. The figure shows that the areas of both the VLD and SHDF platforms are reduced approximately $[d(2+\sqrt{2})/l]^2$ times by folding, whereas the thickness is approximately doubled from l to $2l$, resulting in a packaging efficiency of $\frac{1}{2}(2+\sqrt{2})^{-2}(l/d)^2 = 0.043(l/d)^2$. Although the reduction ratio of the area of the VDF truss platform by folding is the same as that of the VLD and SHDF, the thickness increases approximately from l to $3l$, resulting in a volume ratio of $\frac{1}{3}(2+\sqrt{2})^{-2}(l/d)^2 = 0.029(l/d)^2$. In the case of the BADF, the area reduction ratio is $16(d/l)^2$. However, because the thickness increases to only $\sqrt{2}l$, the resulting volume ratio is $(\sqrt{2}/32)(l/d)^2 = 0.044(l/d)^2$, which is almost the same as those of the VLD and SHDF. (See Table 1.)

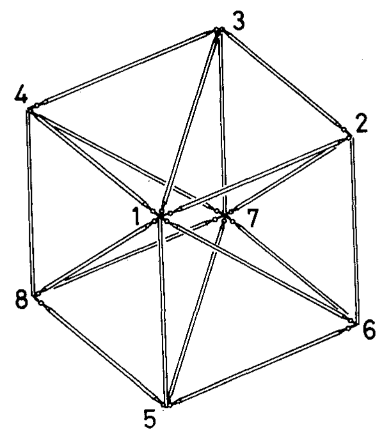

Fig. 6 Fully deployed module of VDF truss.

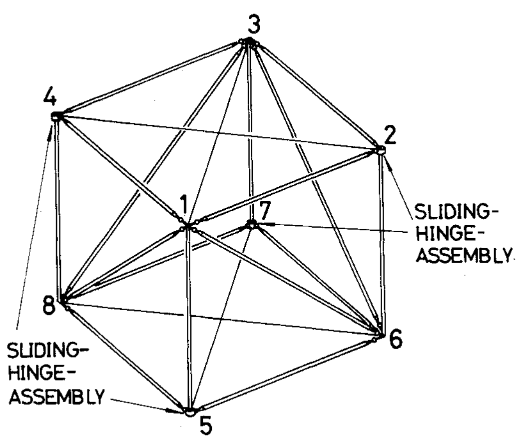

Fig. 7 Fully deployed module of BADF truss.

V. Design Flexibility in Forming a Curved Surface

Necessary Conditions for Folding

Figures 1 and 4 show examples of cubic modules. However, the modules of other shapes, which can be obtained by shifting the location of some nodes, can be folded and deployed; therefore, deployable structures of various overall shapes such as a curved surface can be made. This flexibility in design is also an important factor in the comparison and selection of the concepts. Therefore, the necessary conditions for deployment of the above-mentioned truss structures are investigated in this section.

The four nodal points composing the front or back face of a module of arbitrary shape might not be located in the same plane in the deployed state. If the direction of the deviation of a node from the plane in which the other three nodal points are

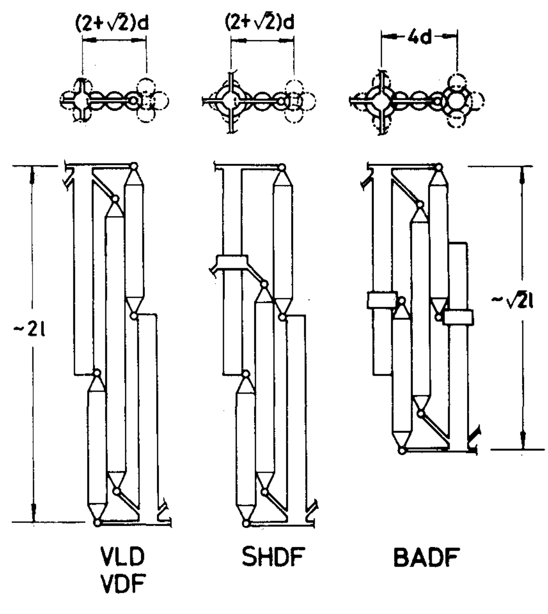

Fig. 8 Most compact folding.

Table 1 Summary of characteristics

Characteristic	VLD	SHDF	VDF	BADF
$\frac{\text{Deployed volume}}{\text{Packed volume}} \times \left(\frac{d}{l}\right)^2$	0.043	0.043	0.029	0.044
No. of mechanisms to be actuated and locked (per module)	2	0.5	4	1
No. of geometrical constraints (per module)	3	4.5	3	4

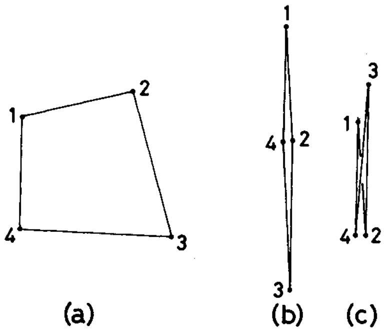

Fig. 9 Folding of a quadrilateral.

located is opposite to that of the folding motion, the face diagonal members need to be elongated at the initial stage of the folding process. However, if the curvature of the overall surface to be formed by the truss is small, the four nodal points will be located in nearly the same plane and, as a result, the necessary elongation for the face diagonal members can be small enough compared to an acceptable elastic elongation. The following discussion is limited to cases where the necessary elongation of the face diagonal members is small enough to be attained by elasticity or to cases in which a device elongates the face diagonal member when, for instance, excessive tension is applied.

When a deployable truss structure is folded and all the members become parallel with each other, all the quadrilaterals composed of four fixed-length members are folded in either of the two manners shown in Fig. 9. In order to be folded as shown in Fig. 9b, it is necessary to have

$$L_{12} + L_{23} = L_{14} + L_{34} \tag{1a}$$

and in order to be folded as shown in Fig. 9c, it is necessary to have

$$L_{12} + L_{34} = L_{14} + L_{23} \tag{1b}$$

where L_{ij} denotes an effective length of the member connecting node i to node j measured along the members in the folded state as shown in Fig. 10.

Therefore, necessary conditions for the module of VDF truss shown in Fig. 6 to be folded can be written as

$$L_{12} + L_{26} = L_{15} + L_{56} \tag{2a}$$

$$L_{23} + L_{37} = L_{26} + L_{67} \tag{2b}$$

$$L_{48} + L_{78} = L_{34} + L_{37} \tag{2c}$$

$$L_{15} + L_{58} = L_{14} + L_{48} \tag{2d}$$

$$L_{12} + L_{23} = L_{14} + L_{34} \tag{2e}$$

It may seem that some more equations must be satisfied; however, they can be derived from Eqs. (2). Similarly, the folding conditions are as follows:

1) For the module of the VLD truss shown in Fig. 1,

$$L_{12} + L_{26} = L_{15} + L_{56} \tag{3a}$$

$$L_{37} + L_{67} = L_{23} + L_{26} \tag{3b}$$

$$L_{34} + L_{48} = L_{37} + L_{78} \tag{3c}$$

$$L_{15} + L_{58} = L_{14} + L_{48} \tag{3d}$$

$$L_{12} + L_{34} = L_{23} + L_{14} \tag{3e}$$

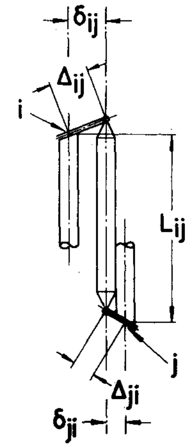

Fig. 10 Folded members and some definition of length.

2) For the module of the BADF truss shown in Fig. 7,

$$L_{16} + L_{58} = L_{18} + L_{56} \tag{4a}$$

$$L_{36} + L_{12} = L_{16} + L_{23} \tag{4b}$$

$$L_{38} + L_{67} = L_{36} + L_{78} \tag{4c}$$

$$L_{18} + L_{34} = L_{38} + L_{14} \tag{4d}$$

$$L_{12} + L_{34} = L_{14} + L_{23} \tag{4e}$$

3) For the module of the SHDF truss shown in Fig. 4, Eqs. (3) plus

$$L_{16} + L_{58} = L_{18} + L_{56} \tag{5a}$$

$$L_{36} + L_{78} = L_{38} + L_{67} \tag{5b}$$

When the modules are arranged in rows and columns into a platform, Eqs. (2a–2d) and (3a–3d) are shared by two adjacent modules because all the members whose lengths appear in any one of them are shared by the two modules. Similarly, if a condition equivalent to any one of Eqs. (4a–4d), (5a), or (5b) is satisfied by three of four adjacent modules sharing a cross member, the condition is automatically satisfied by the other module. Therefore, each of the conditions of Eqs. (2a–2d) and (3a–3d) should be counted as approximately a half-constraint per module and each of the conditions of Eqs. (4a–4d), (5a), and (5b) should be counted approximately three-fourths per module. As a result, each module of the VDF and VLD truss platforms must satisfy approximately three constraints on the length of the members on the average. Similarly, each module of BADF truss platform must satisfy approximately four constraints and that of SHDF truss platform must satisfy approximately four and a half constraints on average. This fact indicates that both VDF and VLD are relatively flexible for use in platforms of various shapes and that SHDF has the least flexibility. These results are summarized in Table 1.

Design Flexibility of VLD and VDF Truss

An example of design process to form an arbitrary shallow surface with VLD trusses is as follows:

1) Determine the locations of nodes along two axes on the imaginary surface as shown in Fig. 11a, such that all distances between any two adjacent nodes are equal to l.

2) Sequentially determine the locations of nodes on the imaginary surface until the nodes cover the total area of the imaginary surface as shown in Figs. 11b–e, such that the distances from the adjacent nodes are all equal to l.

3) Determine the locations of the nodes, each of which is apart from the above-determined nodes with the distance of l in

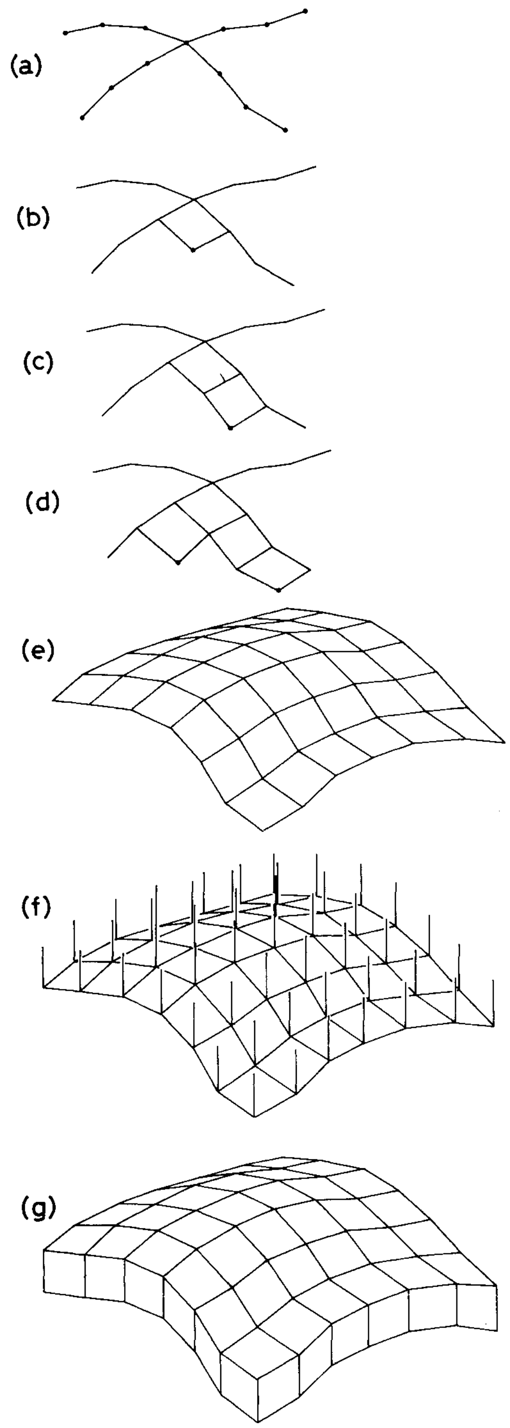

Fig. 11 Design process of VLD and VDF truss forming an arbitrary shallow surface.

a direction globally normal to the imaginary shallow surface as shown in Fig. 11f.

4) Determine the lengths of all the members and the locations of hinges according to the above-determined locations of nodes in the deployed state, such that for all modules,

$$\Delta_{12} = \Delta_{14} = \Delta_{32} = \Delta_{34} = \Delta_{65} = \Delta_{67} = \Delta_{87} = \Delta_{85} = C_1 \quad (6a)$$

$$\Delta_{21} = \Delta_{23} = \Delta_{43} = \Delta_{41} = \Delta_{56} = \Delta_{58} = \Delta_{76} = \Delta_{78} = C_2 \quad (6b)$$

where C_1 and C_2 are constants and Δ_{ij} the offset distance of a hinge from node i to node j measured along the member in the fully deployed state as shown in Figs. 10 and 12.

In the resulting configuration, all the cross members are parallel with each other and their lengths are equal to l. The hinge-to-hinge lengths of all face members are equal to $l - C_1 - C_2$ and all side faces are parallelogram in the fully deployed state. Therefore, considering a typical module shown in Fig. 12, it is clear that

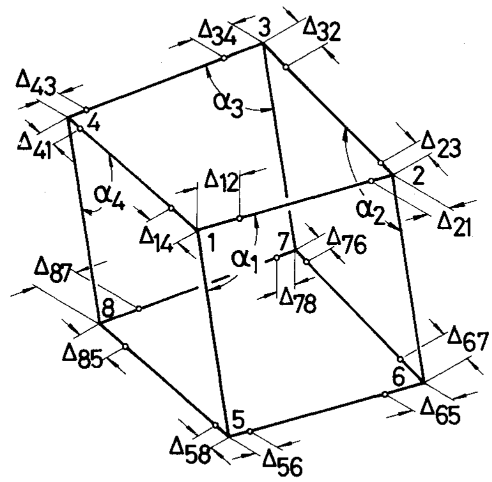

Fig. 12 Module forming an arbitrary shallow surface.

$$L_{12} = L_{56} = l - (C_1 + C_2)(1 - \cos\alpha_1)$$

$$L_{23} = L_{67} = l - (C_1 + C_2)(1 + \cos\alpha_2)$$

$$L_{34} = L_{78} = l - (C_1 + C_2)(1 - \cos\alpha_3)$$

$$L_{14} = L_{58} = l - (C_1 + C_2)(1 + \cos\alpha_4)$$

$$L_{15} = L_{26} = L_{37} = L_{48} = l$$

$$\cos\alpha_1 + \cos\alpha_2 + \cos\alpha_3 + \cos\alpha_4 = 0 \quad (7)$$

where α_1, α_2, α_3, and α_4 are the angles between the cross members and face members in the fully deployed state as shown in Fig. 12. Since these equations are satisfied, Eqs. (3) are also satisfied. It is also clear that all of the node locations can be determined in the above-mentioned manner if the imaginary surface is not very deep and the radius of curvature is large compared with the length of the element.

From this design process, it is obvious that the VLD truss structures have sufficient design flexibility for forming an arbitrary, shallow curved surface. It can be seen that a VDF truss structure forming an arbitrary shallow curved surface can be designed in similar manner.

Design Flexibility of SHDF and BADF Trusses

It can be seen from a geometrical investigation, shown in the Appendix, that a shallow spherical surface can be formed by SHDF. However, it is more interesting to investigate if a globally parabolic surface can be made by the deployable truss, because a huge space antenna is one of the most attractive applications for a deployable truss that can form a curved surface.

In order to investigate whether a macroscopic parabolic surface can be formed by a SHDF truss, which has the least design flexibility among the four above-mentioned types, the locations of the nodes were determined by a numerical calculation such that Eqs. (3), (5), and the following equations were satisfied as much as possible in a least-square sense with the assumptions mentioned in the Sec. IV:

$$l(i,j,0;i+1,j,0) = l(i,j,0;i,j+1,0) = l \quad (8a)$$

$$z(i,j,0) = -\{x(i,j,0)^2 + y(i,j,0)^2\}/(20l) \quad (8b)$$

$$z(0,0,1) = l \quad (8c)$$

$$x(0,j,0) = x(0,j,1) = y(i,0,0) = y(i,0,1) = 0 \quad (8d)$$

$$-3 \le i \le 3, \quad -3 \le j \le 3$$

where $x(i,j,k)$, $y(i,j,k)$, and $z(i,j,k)$ denote the location of node (i,j,k) in a Cartesian coordinate [node (i,j,k) is that in the ith column and jth row of the front ($k = 1$) or back ($k = 0$) surface] and $l(i,j,k;l,m,n)$ denotes the distance between nodes (i,j,k) and (l,m,n) in the fully deployed state. For all modules it is assumed that

$$\begin{aligned}\delta_{12} = \delta_{14} = \delta_{32} = \delta_{34} = \delta_{65} = \delta_{67} = \delta_{87} = \delta_{85} = (4+\sqrt{2})l/100 \\ \delta_{21\mathrm{fl}} = \delta_{23} = \delta_{43} = \delta_{41} = \delta_{56} = \delta_{58} = \delta_{76} = \delta_{78} = \sqrt{2}l/100 \\ \delta_{16} = \delta_{61} = \delta_{36} = \delta_{63} = \delta_{38} = \delta_{83} = \delta_{18} = \delta_{81} = (2+\sqrt{2})l/100\end{aligned} \tag{9}$$

where δ_{ij} is the offset of a hinge from node i to node j measured normal to the cross members as shown in Fig. 10 and the nodal numbers shown in Fig. 4 are used. Equations (9) approximately correspond to the most compact folding of the truss composed of members whose diameter is slightly less than $l/50$. Figure 13 shows an example of resulting truss structure composed of 6×6 modules. Subsequently, the position of the sliding-hinge assemblies in the mathematical model were moved and the half-folded/deployed configurations were obtained by similar iterative calculations in order to confirm the kinematic consistency of the truss' deployment/folding process. Figure 14 shows an example of the results where the central sliding-hinge assembly is driven 90% from the full-deploy position to the full-fold position.

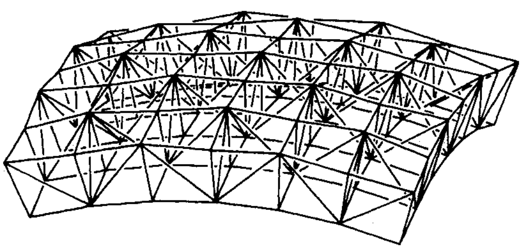

Fig. 13 SHDF truss forming a parabolic surface.

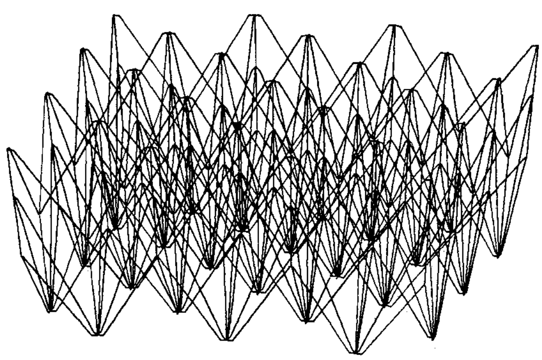

Fig. 14 Deploy/fold process of SHDF truss forming a parabolic surface.

Although the locations of the nodes of the structure shown in Fig. 13 do not satisfy the above equations in a very strict sense, the errors were very small. In this particular example, the rms value of the error for Eqs. (3) and (5) was $3.0 \times 10^{-6}l$ and for Eq. (6b) $5.2 \times 10^{-4}l$ when the iterative calculations were terminated. Similarly, the difference in the length of the corresponding members of the truss structure between Fig. 13 and the numerically obtained half-deployed/folded configurations was $7.5 \times 10^{-6}l$ when the iterative calculations were terminated in the worst case. Furthermore, the necessary elongation for the face diagonal members at the initial stage of folding process was found to cause only about 10^{-6} strain in the worst case. Since an error in length of the order of $10^{-5}l$ can be easily adjusted by an elastic deformation of the members and the shape error of the order of $10^{-3}l$ can be easily compensated for by adjusting the attachment points of the reflector mesh of antenna, the structure shown in Fig. 13 can be regarded as a demonstration of the fact that a parabolic surface can be formed by a SHDF truss with sufficient accuracy.

In order to investigate the design flexibility of the BADF truss, a similar calculation was carried out. The results were similar to the SHDF truss: the rms value of error for Eqs. (4) was $6.1 \times 10^{-6}l$ and for Eq. (6b) $5.0 \times 10^{-4}l$ when the iterative calculations were terminated. These facts suggest that both SHDF and BADF have practically acceptable design flexibility, although they have less design flexibility than VLD and VDF.

VI. Construction of Functional Model

In order to demonstrate the practicality of the present concepts of two-dimensional deployable trusses, a model of each type was fabricated. Figure 15a shows the fabricated model of the VLD truss platform in the fully deployed state, whereas Figs. 15b and 15c show the model in half-deployed/folded and fully folded states, respectively. The driving force for deployment is provided by springs installed within the variable-length diagonal members and at the hinges. Each variable-length diagonal member is provided with a lock mechanism that fixes the length after deployment.

Figure 16a shows the fabricated model of SHDF truss platform in the fully deployed state. The mode in the half-deployed/folded state and fully folded states is shown in Figs. 16b and 16c, respectively. As shown in Figs. 17 and 18,

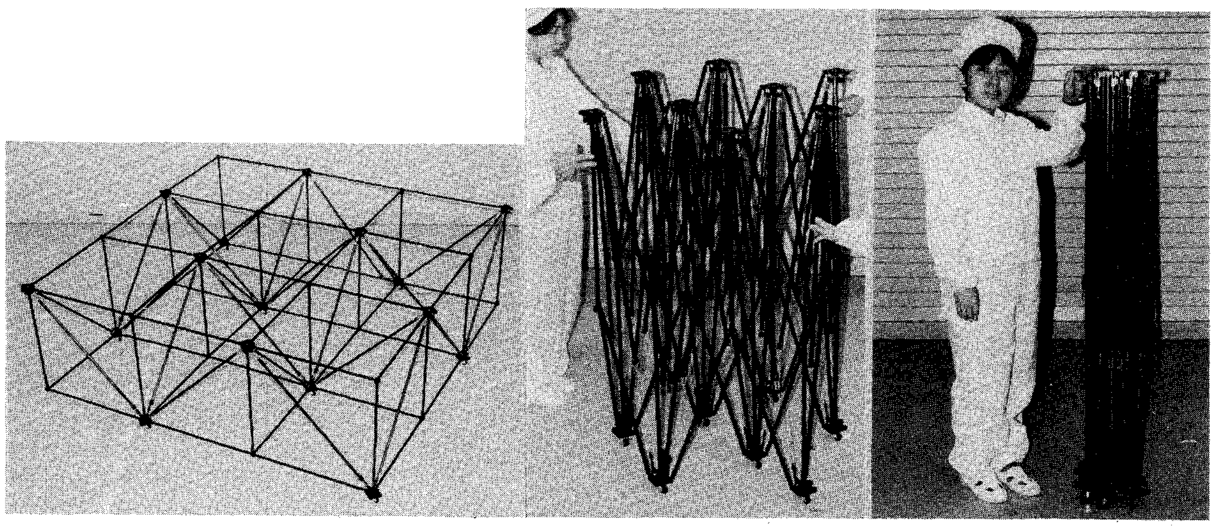

Fig. 15 VLD platform model fabricated for trial.

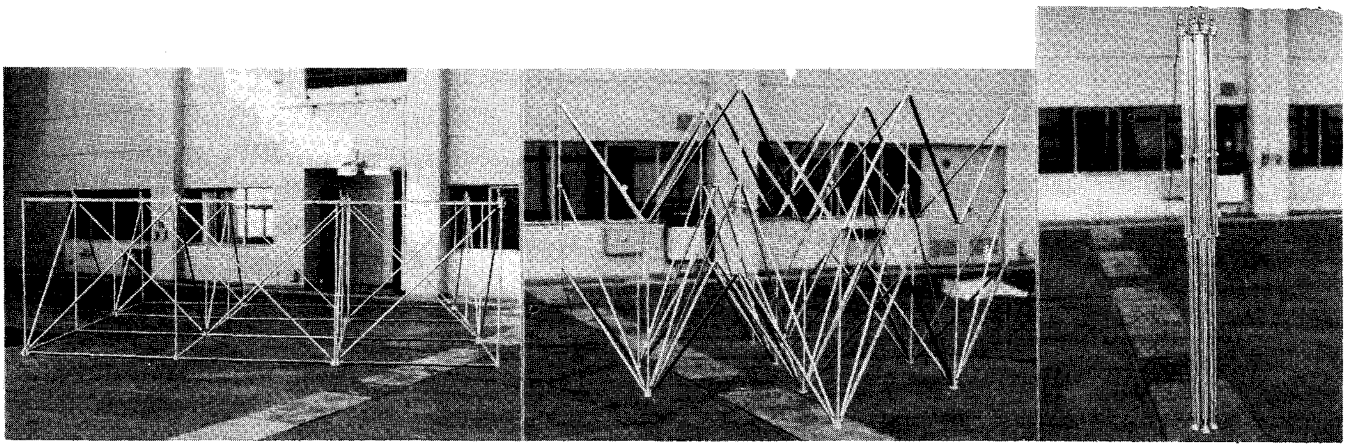

Fig. 16 Deploy/retract test using a SHDF platform model.

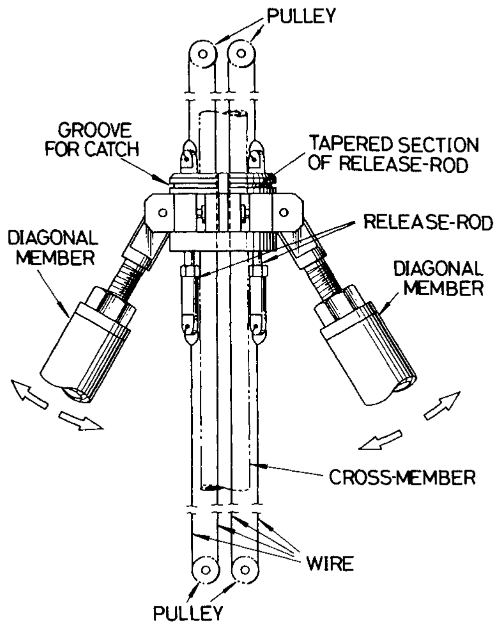

Fig. 17 Sliding-hinge assembly.

each sliding-hinge assembly is driven by two loops of wires that, in turn, are actuated by a tiny electromagnetic motor installed on the hinge assembly fixed to the front end of the cross member on which the sliding-hinge assembly is mounted. The fixed-hinge assembly has a lock mechanism (i.e., a pair of catches) that holds the sliding-hinge assembly against itself when the platform is fully deployed. The release rods shown in Fig. 17 can move slightly relative to the sliding-hinge assembly. When the release rods are reversely pulled by the motor, tapered sections of the rods push up the catches, releasing the lock. Therefore, the platform can be not only deployed, but also folded automatically by the motors. In order to assist the initial motion of deployment, small springs are also installed at the hinges.

In order to confirm that the platform models can actually be deployed/retracted without difficulty, deployment/retraction tests were conducted. The platforms were hung by long flexible expandable strings at the center of the front face members so that gravity did not contribute much to the deployment/retraction motion. The SHDF platform model was deployed and subsequently retracted by the action of the motors, while the VLD model was deployed only by the spring force. In all of the tests, smooth and substantially synchronized motion was confirmed. It seemed that the slight nonuniformity in the actuating force and/or the friction does not disturb the synchronous motion much because the advanced motion in an actuator assists delayed motion of another actuator.

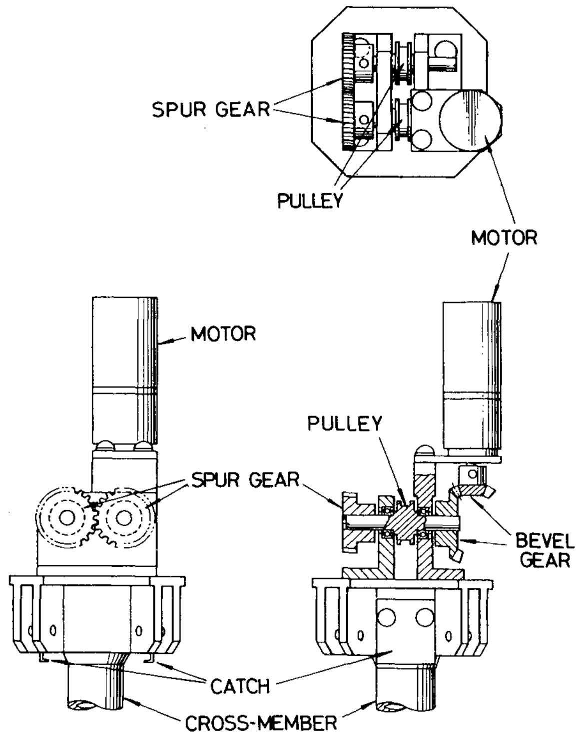

Fig. 18 Fixed-hinge assembly and the actuation device for the nodes 1 and 3 of Fig. 4.

VII. Derivative Versions

Slight modification of the basic module structures proposed above can result in modules with other desirable properties, for example, the replacement of flexible face diagonal members by articulated rigid members without lock mechanisms at the central hinges. Another modification is the replacement of each pair of flexible face diagonal members by an articulated rigid diagonal member. This version requires a central hinge with a lock mechanism on each face diagonal member, resulting in an increased number of mechanisms. The number of mechanisms to be actuated and locked at the deployment of this VLD-derived version is four per module, which is the same as that of VDF. However, this version still has an advantage in packaging density over the VDF. The number of mechanisms for this version derived from SHDF is 2.5 per module. Furthermore, since most of two-dimensionally deployable truss structures are statically indeterminant, some members can be eliminated if desired.

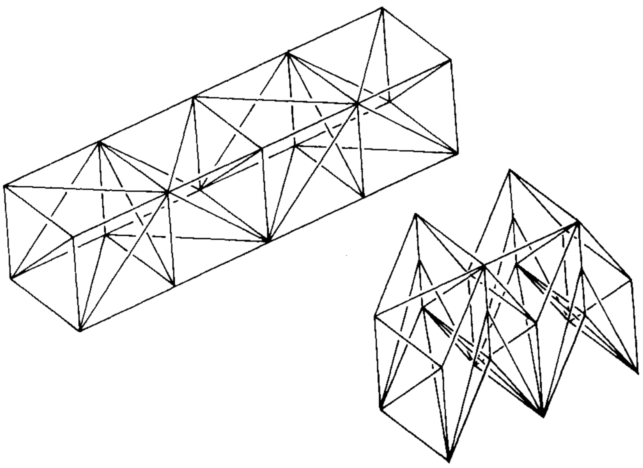

Fig. 19 SHSF deployable truss.

Another version is a one-dimensional deployable truss shown in Fig. 19, which is derived from SHDF and may be called a sliding-hinge single-fold (SHSF) truss. It is possible to make a one-dimensional deployable truss by using a linear part of any two-dimensional deployable structures. However, a single-fold truss such as SHSF, whose cross-sectional geometry does not vary during deployment/retraction, is desirable if it is to be deployed from another structure. It should be noted that the number of the mechanisms on this truss to be actuated/locked is small. A combination of, e.g., SHDF and SHSF is a conveniently deployable surface from another structure.

VIII. Conclusions

Two concepts of a two-dimensional deployable truss, namely, a variable-length diagonal (VLD) and a sliding-hinge double-fold (SHDF) truss, have been presented. They have the advantage in that they have no articulated members whose central hinges might reduce the Euler buckling strength.

Some features of the present deployable structures are discussed in comparison with the existing VDF and BADF trusses and summarized in Table 1. The advantages of the proposed deployable truss structures over the existing ones are as follows:

1) Compared with VDF, the VLD truss requires only half the number of mechanisms to be actuated and locked at deployment, has better packaging efficiency, and exhibits the same design flexibility.

2) Compared with BADF, the SHDF truss has only half the number of mechanisms, almost the same packaging efficiency, and slightly less design flexibility. Although SHDF has the least design flexibility of the four concepts, it can form a globally parabolic surface with acceptable accuracy.

The deployment/retraction tests of the present deployable truss platforms demonstrated relatively synchronized motion without difficulty.

Appendix: Design Method for a SHDF Platform Forming a Globally Spherical Surface

As shown in Fig. 11, it is always possible to locate all the nodes $(i,j,0)$, i.e., the nodes on the back surface of a platform, exactly on an imaginary shallow spherical surface, such that

$$l(i,j,0;i,j+1,0) = l(i,j,0;i+1,j,0) = l_1 \tag{A1}$$

Let a sliding-hinge assembly be mounted on the member $(h,k,0;h,k,1)$ where $h+k$ is even, and let us locate the node $(h,k+1,1)$ on the line drawn from point C through node $(h,k+1,0)$ as shown in Fig. A1 such that, e.g.,

$$l(h,k+1,0;h,k+1,1) = l_1 \tag{A2}$$

where point C denotes the center of the imaginary sphere. It is

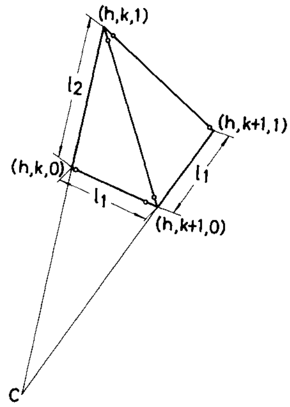

Fig. A1 Determination of the locations of nodes of SHDF truss forming a spherical surface.

possible to select the location of the node $(h,k,1)$ on the line drawn from C through node $(h,k,0)$ such that

$$L(h,k,0;h,k+1,0) + l(h,k,0;h,k,1) = L(h,k,1;h,k+1,1) + l_1 \tag{A3}$$

where $L(i,j,k;l,m,n)$ denotes the effective length of the member connecting node (i,j,k) to node (l,m,n) in the same sense as L_{ij} defined in Sec. V. Let the resulting value of $l(h,k,0;h,k,1)$ be l_2 and let us locate the node $(i,j,1)$ on the line drawn from point C through node $(i,j,0)$ such that

$$l(i,j,0;i,j,1) = l_1 \quad (\text{if } i+j \text{ is odd})$$
$$l(i,j,0;i,j,1) = l_2 \quad (\text{if } i+j \text{ is even}) \tag{A4}$$

Then, it is clear that all side faces of all modules have the same configuration because of the axisymmetry of an arbitrary line drawn from point C. Therefore, if the offset distances are the same for all side faces of the modules, it can be seen that the resulting truss structure satisfies Eqs. (3) and (5).

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