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Two-Dimensionally Deployable "SHDF" Truss*

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Summary: The present paper describes a newly invented two-dimensionally deployable truss structure named SHDF, which has no articulated members. The most significant feature of SHDF truss is the very small number of the mechanisms to be actuated and locked at the deployment. A globally flat functional model actuated by tiny electromagnetic motors was designed and fabricated. The model demonstrated its practicality and virtually synchronized smooth motion in deploy/fold tests. Subsequently, the model was reformed into a globally parabolic configuration and combined with a one-dimensionally deployable truss named SHSF, which is also newly invented. Further deploy/fold tests similarly demonstrated the practicality of parabolic SHDF truss structure and the compatibility of SHDF with SHSF.

key words: Space structure, Deployable structure, Truss structure.

1. INTRODUCTION

For the construction of a large space structure, its structural components must be packaged in a compact volume in order to accommodate to the size of the cargo bay which will deliver them to the space. Further compact packaging could be desirable in many cases when the volume, rather than the weight, dominates the transportational cost of light-weight large-volume structural component. Reduction of the construction-related space activity is also desirable because it will be extremely costly as compared with the ground construction activity. One of the most attractive techniques which satisfy these two requirements is the usage of deployable structures which are packaged in a very compact volume while they are transported and can be automatically deployed to the final structural configurations in the orbits. Therefore, many types of deployable truss have been proposed and, to some extent, developed involving two-dimensionally deployable ones [*1–10*].

Each deployable truss has its own advantages and disadvantages, and therefore the most suitable one should be selected for each specified application. Therefore, it is important to develop, investigate and evaluate as many kinds of deployable trusses as possible. One of the authors has proposed new concepts for two-dimensionally

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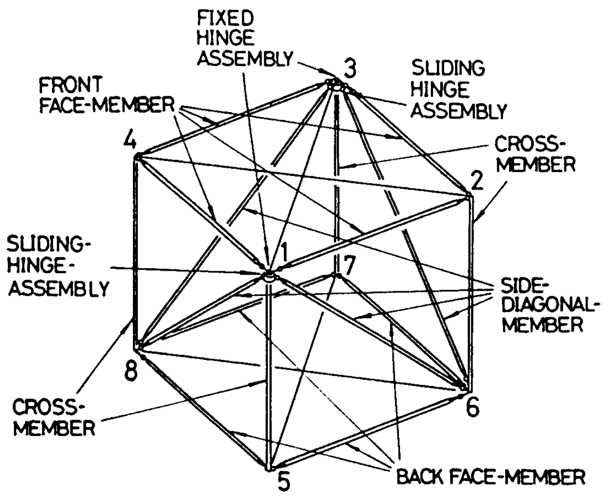

Fig. 1. A Fully Deployed Module of SHDF Truss.

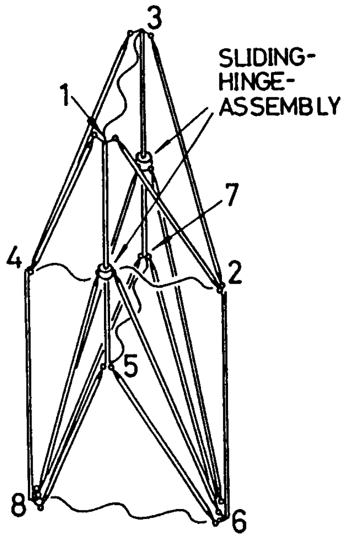

Fig. 2. A Half Folded/Deployed Module of SHDF Truss.

deployable trusses involving the Sliding Hinge Double Fold (SHDF) truss [*9,10*]. In this paper, the concept of SHDF truss and its features are briefly introduced, and subsequently, the design, fabrication, and the testing of the functional models are described.

2. Basic Concept of SHDF Truss

Figure 1 shows a basic module of the SHDF truss in a fully deployed state. The module is composed of eight rigid face-members placed along the edges of front and back faces of an imaginary rectangular parallelepiped, four rigid cross-members placed along the other edges, two pairs of flexible face-diagonal-members extending along the diagonal lines in the front and back faces, four rigid side-diagonal-members, eight fixed-hinge-assemblies at each end of the cross-members and two sliding-hinge-assemblies mounted on two cross-members. One end of each side-diagonal-member is pivotally connected to a fixed-hinge-assembly, and the other end is similarly fixed to a sliding-hinge-assembly. All the other rigid members except for the cross-members are pivotally connected to the fixed-hinge-assembly at the ends. When the truss is fully deployed as shown in Fig. 1, the sliding-hinge-assemblies are held against the fixed-hinge-assemblies. As the sliding-hinge-assemblies are slid away from the fixed-hinge-assemblies against which they were held, the module is collapsed as shown in Fig. 2, and finally, it is packed in a very compact volume. Conversely, it is re-deployed by the reversal sliding of the sliding-hinge-assemblies.

It is obvious that a two-dimensional truss (considering the structure as a whole) composed of a plurality of the modules arranged in rows and columns as shown in Fig. 3 can also be collapsed into a compact volume and re-deployed in the same manner as shown above.

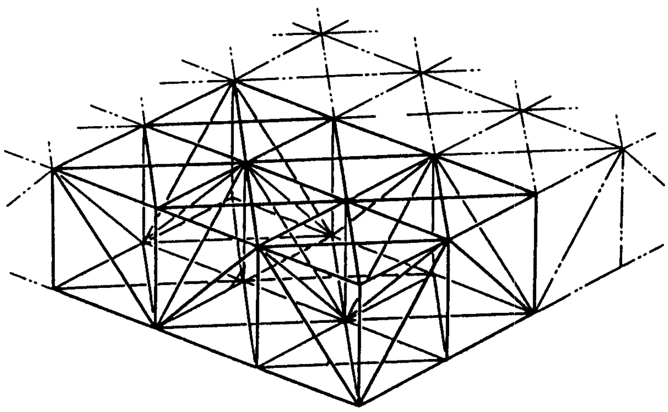

Fig. 3. A SHDF Truss Platform Composed of a Plurality of Modules.

Table 1. A comparison of SHDF with other two-dimensionally deployable trusses.

	SHDF	VDF	BADF	PKT	MBT
$\frac{\text{deployed volume}}{\text{packed volume}} \times \left(\frac{d}{l}\right)^2$	0.043	0.029	0.044	0.036*	0.111
number of mechanisms to be locked per module	0.5	4	1	4	4
number of geometrical constraint per module	4.5	3	4	3	—

VDF =Vought Double Fold (Ref. 1)
BADF=Vought Biaxial Double Fold (Ref. 1)
PKT =PACKTRUSS (Ref. 7)
MBT =Martin Marietta Box Truss (Ref. 5)
*This value is for platforms composed of cubic modules although only skew ones are shown in Ref. 7.

3. Features of SHDF Truss

A feature of SHDF truss is that it can be folded/deployed by the sliding of the sliding-hinge-assemblies only. Many of the existing deployable truss structures are folded by bending some articulated members at the center hinges. However, the center hinges could induce geometrical imperfection and reduce the rigidity at the center hinge, resulting in a reduction of Euler buckling strength. The SHDF truss has no such articulated members. A version of Vought Biaxial Double Fold (BADF) truss [*1*] is the only existing two-dimensionally deployable truss which can be folded/deployed by sliding hinge assemblies.

Another feature, which is most significant, is the very small number of the mechanisms to be actuated and locked at the deployment. The number of sliding-hinge-assemblies is approximately one-half per module in an average because each sliding-hinge-assembly is shared by four modules when a plurality of the modules are arranged into a two-dimensional structure. Table 1 comparatively shows the

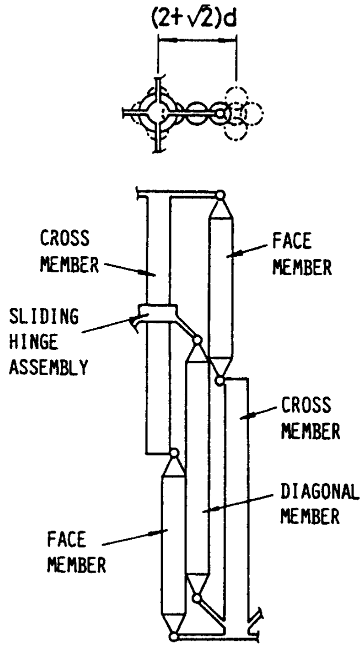

Fig. 4. Most Compactly Folded Side Face of a SHDF Truss Module.

numbers of mechanisms of several typical types of deployable structures together with that of SHDF. Reducation of the number of the mechanisms to be actuated at the deployment and to be locked at the deployed state is very important for deployable trusses because a larger number of such mechanisms not only increases the total weight but also decreases the reliability of deployment.

Another important performance index for deployable truss structures is the packaging efficiency, which is defined as the ratio of the volume of the deployed structure to that of folded structure. The packaging efficiency of several types of deployable truss structures can be calculated as shown in Table 1 under the following assumptions:

1) The deployed configuration of all modules is a cube whose edges are l in length.
2) All the rigid members are tubes whose diameters are d.
3) The axes of the members intersect with each other at the nodal points.

The value for SHDF, for example, can be derived from Fig. 4 which shows a most compactly folded side-face of a module. It can be seen that the distance between the axes of two adjacent cross-members can not be less than $(2+\sqrt{2})d$ in the folded state. The table shows that the packaging efficiency of SHDF is superior or almost equal to the others except for the MBT [5].

4. Design Flexibility

Figure 1 shows an example of a cubic module. However, modules of other shapes, which can be derived by shifting the location of some nodes and varying the length of some members, can be folded and deployed. Therefore, deployable structures of various shapes such as a curved surface can be made by arranging such modules. This

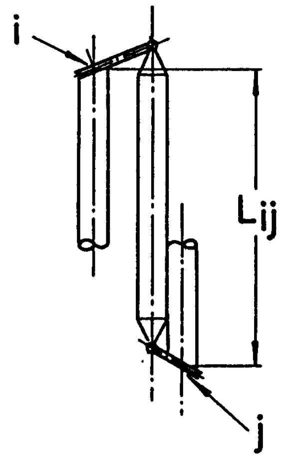

Fig. 5. Effective Length of the Member Connecting Node i to Node j.

design flexibility is sometimes important for the deployable structures.

Necessary condition for the module of SHDF shown in Fig. 1 to be folded can be written as

$$L_{12} + L_{26} = L_{15} + L_{56} \quad (1)$$
$$L_{37} + L_{67} = L_{23} + L_{26} \quad (2)$$
$$L_{34} + L_{48} = L_{37} + L_{78} \quad (3)$$
$$L_{15} + L_{58} = L_{14} + L_{48} \quad (4)$$
$$L_{12} + L_{34} = L_{23} + L_{14} \quad (5)$$
$$L_{16} + L_{58} = L_{18} + L_{56} \quad (6)$$
$$L_{36} + L_{78} = L_{38} + L_{67} \quad (7)$$

where, L_{ij} denotes the effective length of the member connecting node i to node j measured parallel to all the rigid members in a fully folded state as shown in Fig. 5 [*10*]. When the modules are arranged in rows and columns into a platform, Eqs. (1–4) are sheared by two adjacent modules because all the members whose length appear in any one of the equations are shared by the two modules. Therefore, each of the conditions of Eqs. (1–4) should be counted as approximately a half constraint per module. Let a module A composed of nodes 1–8 is arranged adjacent to the modules B-D as shown in Fig. 6, where module B is composed of nodes 1, 2, 3′, 4′, 5, 6, 7′, 8′, module C of nodes 1, 2′, 3″, 4′, 5, 6′, 7″, 8′, module D of nodes 1, 2′, 3‴, 4, 5, 6′, 7‴, 8′. Then the conditions for modules B-D equivalent to Eq. 6 are

$$L_{16} + L_{58} = L_{18'} + L_{56} \quad (8)$$
$$L_{16'} + L_{58'} = L_{18'} + L_{56'} \quad (9)$$
$$L_{16'} + L_{58} = L_{18} + L_{56'} \quad (10)$$

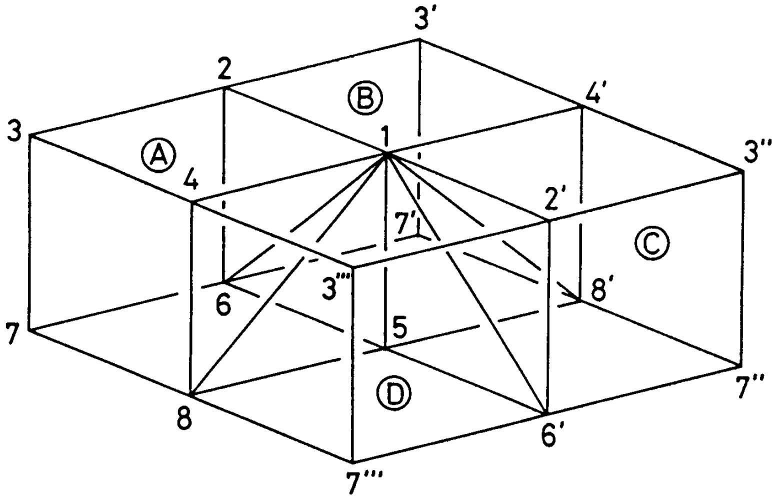

Fig. 6. Arranged Modules.

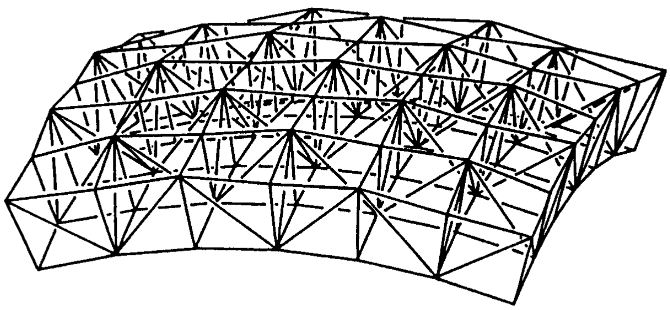

Fig. 7. A Parabolic SHDF Truss.

respectively. It can be seen, for example, that Eq. (6) can be derived from Eqs. (8–10). In other words, Eq. (6) is automatically satisfied by module A if the other three adjacent modules satisfy the condition equivalent to Eq. (6). Therefore, Eq. (6) should be counted as approximately three forth constraint per module. Similarly, Eq. (7) should also be counted as approximately three forth constraint per module. As a result, the effective number of the geometrical constraints per module can be calculated as 4.5 in an average for two-dimensional truss structures composed of infinite number of modules. Table 1 compares the effective number of such geometrical constraints with those of some other types of deployable truss and shows that SHDF has least design flexibility among them. Generally, smaller number of mechanisms in deployable truss seems to result in less design flexibility.

In order to prove that SHDF truss still has sufficient design flexibility for practical application, globally parabolic SHDF truss shown in Fig. 7 was designed. The length of all the rigid members on the concave surface was l, and the focal distance was $5l$. An interative numerical calculation was carried out such that Eq. (7) were satisfied and all the nodes on the concave surface of SHDF truss structure were placed on an imaginary parabolic surface as much as possible in a least square sense. The result demonstrated that a parabolic surface can be formed by SHDF truss with high accuracy. The RMS value of the error, in this particular example, was $3.0\times10^{-6}l$ for

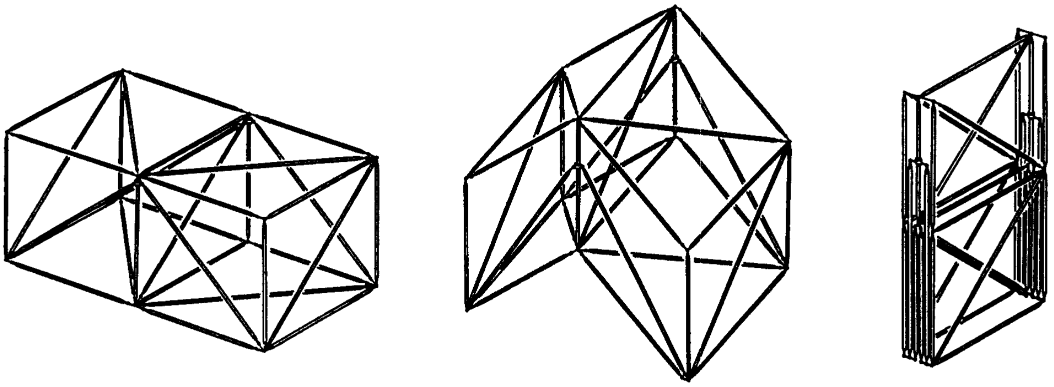

Fig. 8. A SHSF Truss.

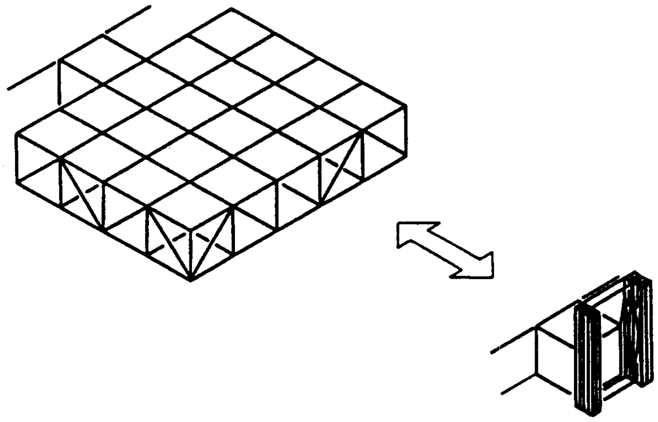

Fig. 9. A Combination of SHDF and SHSF Trusses.

Eq. (1), and that for parabolic shape accuracy was $5.2\times10^{-4}l$ when the iteration was terminated. This fact suggests that SHDF truss has sufficient design flexibillity for practical applications [*10*].

5. SHSF Version

By relocating a sliding-hinge-assembly to another cross-member SHDF truss module, a one-dimensionally deployable truss, which may be called as Sliding Hinge Single Fold (SHSF) truss, can be derived as shown in Fig. 8. It is clear that SHDF truss can be connected to SHSF truss. Since the globally cross-sectional shape of SHSF does not vary during the deployment/folding as can be seen in the figure, the combination of SHDF truss and SHSF is convenient to deploy a truss structure from another structure as shown in Fig. 9.

6. Functional Model of Flat SHDF Truss

6.1 Basic Design

In order to demonstrate the practicality of the concept and the kinematic consistency of SHDF, a flat model composed of 9 cubic modules was fabricated. For

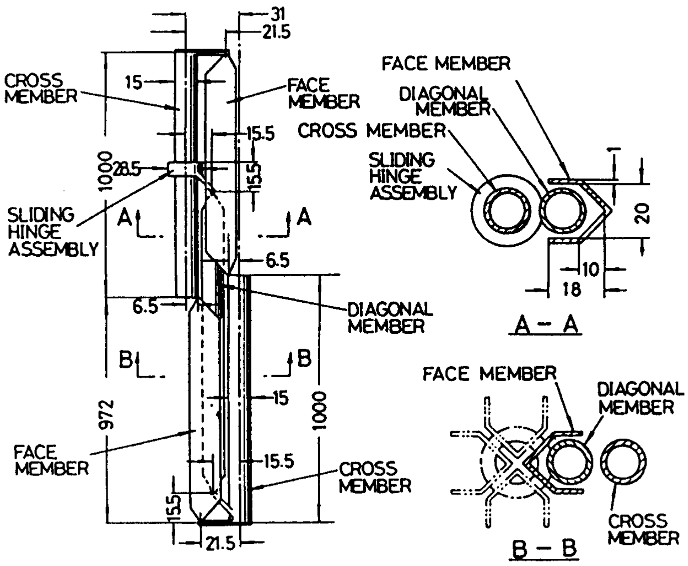

Fig. 10. Nesting Scheme and Dimensions of the Model Components. (unit=mm)

this reason, it was not designed for space use. All the rigid members and fixed-hinge-assemblies were made of aluminum alloy. The truss structure was designed so that it can be deployed/folded by tiny electromagnetic motors.

In this fabrication, face members with V-shaped cross-section were used so that side-diagonal-members can be nested in them in the fully folded condition as shown in Fig. 10. The figure shows that the truss structure can be folded by this method in a more compact volume than that shown in Fig. 4, resulting in a higher packaging efficiency. In this design, the dimensions shown in the figure were used although it is not the configuration of most compact packaging. By applying this nesting scheme, the packaging efficiency of 520 has been attained in the present model while 191 was the best value for the truss composed of tubular members.

6.2 Details of the Structure

Figure 11 shows a fixed-hinge-assembly against which a sliding-hine-assembly is held in the fully deployed state (i.e., nodes 1 and 3 of Fig. 1). Four single-degree-of-freedom hinges are equipped for the connection with the face members. A tiny electromagnetic motor and two motor-driven pulleys are installed on the hinge-assembly. Each pulley drives a loop of wire, which is connected to the sliding-hinge-assembly. Two catches are also mounted on the hinge-assembly in order to hold the sliding-hinge-assembly in the fully deployed state. The sliding-hinge-assembly loosely fits to the cross-member so that it can easily slide along the cross-member. However, the cross-member is tapered at the top end as shown in the figure, and the clearance between the sliding-hinge-assembly and the fixed-hinge-assembly can be neglected when they contact with each other. Figure 12 shows the other end of the cross-member (i.e., nodes 5 and 7 of Fig. 1). The hinge assembly has four single-degree-of-freedom hinges for the face members and two pulleys for the loops of wire.

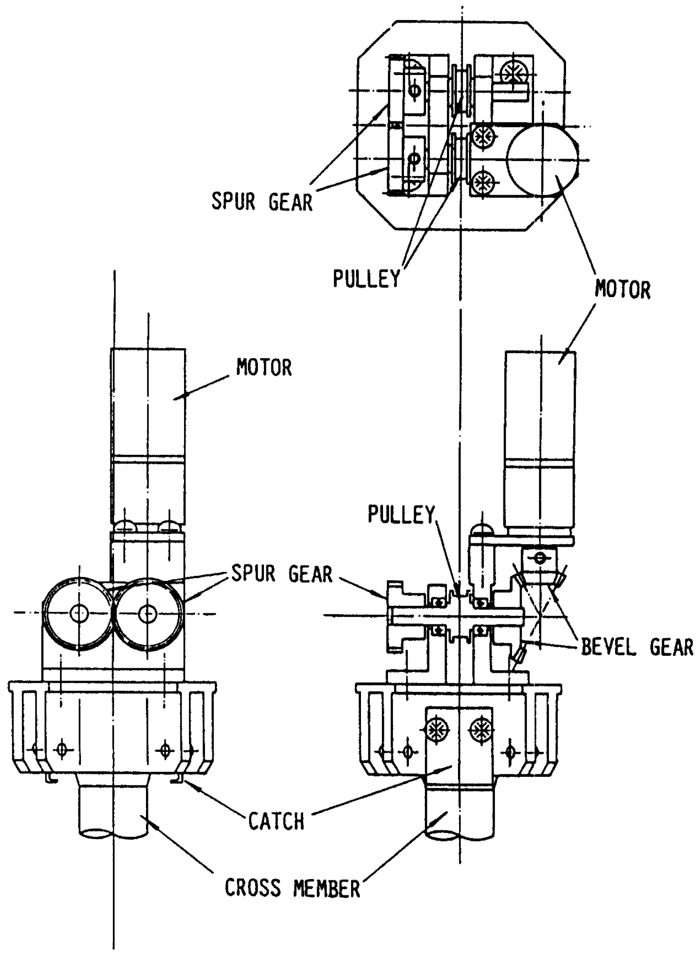

Fig. 11. The Fixed-Hinge-Assembly for Nodes 1 and 3 of Fig. 1.

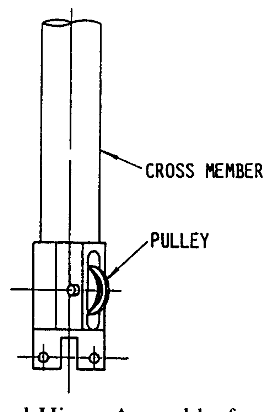

Fig. 12. The Fixed-Hinge-Assembly for Nodes 5 and 7 of Fig. 1.

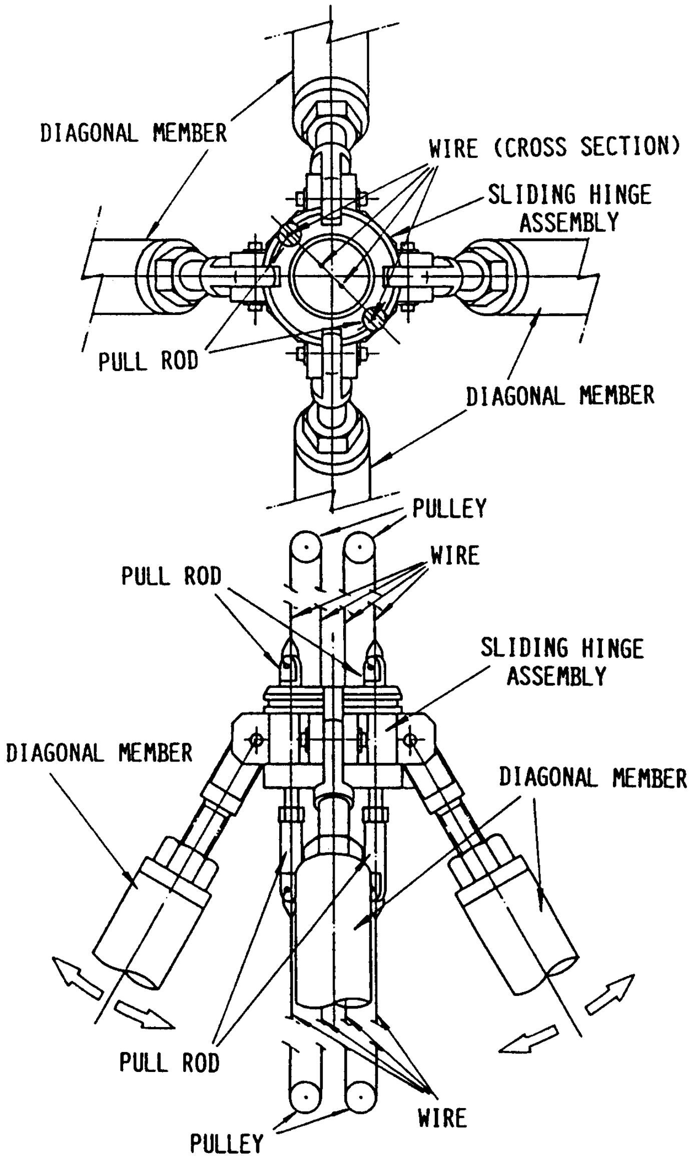

Fig. 13. A Sliding-Hinge-Assembly.

Figure 13 shows a sliding-hinge-assembly, which is driven by the above-mentioned two loops of wire. When it reaches contact with a fixed-hinge-assembly, the catches of the fixed-hinge-assembly fall into the groove of the sliding-hinge-assembly as shown in Fig. 14, holding it against the fixed-hinge-assembly. However, when the loops of wire are reversely driven by the motor, the pull-rods are first pulled reversely, and their tapered sections push up the catches as shown in the figure, releasing the lock. Subsequently, the sliding-hinge-assemblies are slid away from the fixed-hinge-assembly resulting in the folding of the truss. It has been shown that high-rigidity locking mechanism is not needed [9].

The fixed-hinge-assembly for the nodes 6 and 8 of Fig. 1 is shown in Fig. 15. It has eight single-degree-of-freedom hinges, i.e., four for face-members and four for the side-diagonal-members. The hinge-assembly for the nodes 2 and 4 is the same as

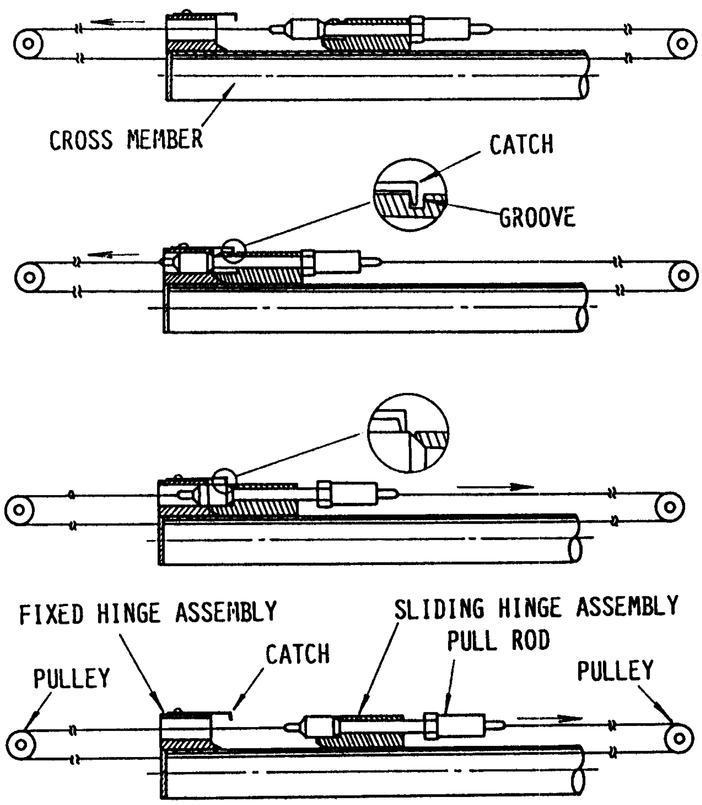

Fig. 14. The Lock/Release Mechanism.

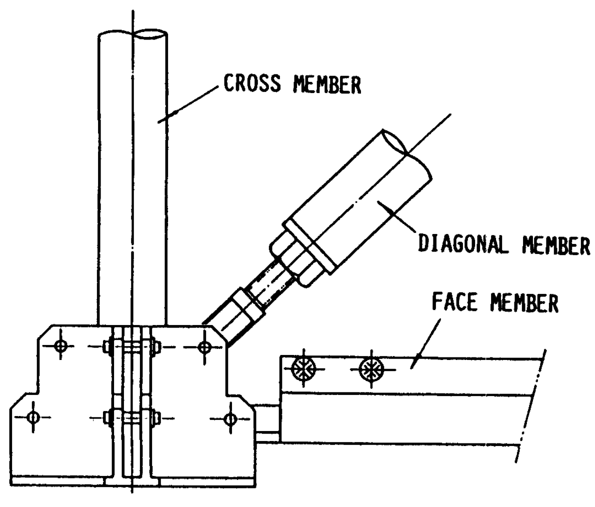

Fig. 15. The Fixed-Hinge-Assembly for Nodes 6 and 8 of Fig. 1.

shown in Fig. 12 expect that it has no pulleys.

In the fully folded state, the force applied to the sliding-hinge-assembly by the motor does not act effectively to deploy the truss because all the truss members are parallel with each other in this condition. Therefore, tiny springs were installed at some hinges so that they assist the initial motion of deployment.

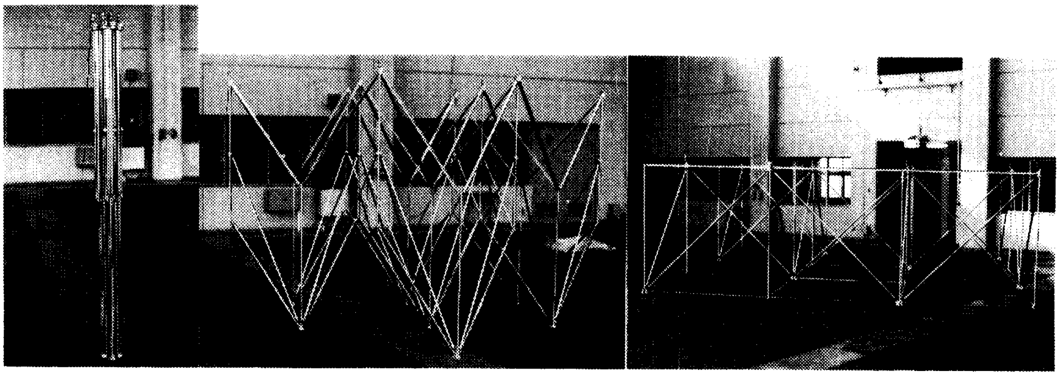

Fig. 16. Deployment/Folding Test of a SHDF Platform.

It can be seen that, for example, $dl_{13}/d\delta \propto \delta/l$ when $\delta/l \ll 1$, where, l_{ij} denotes the distance between node i and j, δ the distance between the sliding-hinge-assembly and the fixed-hinge-assembly and l the nominal length of the cross-members. This fact means that high pre-tension can be generated in the face-diagonal-members by a relatively low-capability small motors.

6.3 Test

Tests were conducted on the SHDF model in order to confirm that this model can be actually deployed/folded without any difficulty. The model was hung by long expandable strings at the midpoints of all the upper surface-members in order to decrease the effect of gravity. The length of the strings were approximately 11m.

Firstly, the truss was fully folded and tied up by a string. Afterwards, the string was cut by electric current in the hung condition, and the motors were actuated electrically. In a few minutes, the model was fully deployed showing a substantially synchronized motion, and the sliding-hinge-assemblies were locked. Subsequently, the motors were actuated reversely, and the model was folded automatically into almost fully folded state. Figure 16 shows the fully folded, half deployed, and fully deployed model in the deployment test. In all 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 very much because an advanced motion in an actuator assists the motion of other delayed actuators.

7. Functional Model of Parabolic SHDF/SHSF Truss

7.1 Basic Design

In order to demonstrate the paracticality of parabolic SHDF truss and the consistency of SHDF with SHSF, the above mentioned flat model was reformed into a parabolic configuration and combined with a SHDF truss. The combined model was approximately a quarter of the primary reflector of the antenna shown in Fig. 17, which can be two-dimensionally folded around the central main body of the satellite and redeployed as shown in Fig. 18.

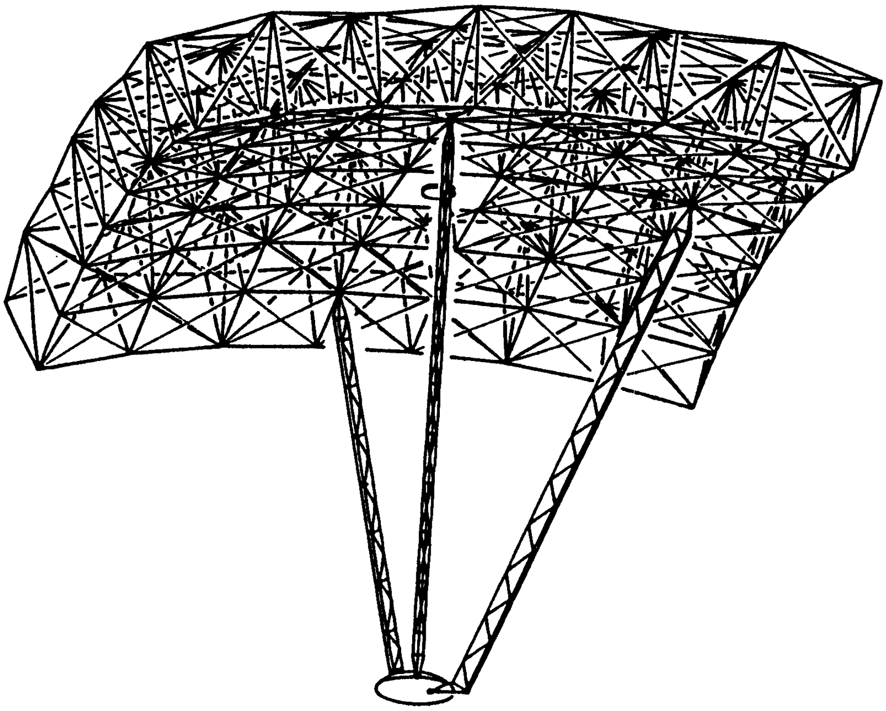

Fig. 17. A Huge Space Antenna Composed of SHDF and SHSF Trusses.

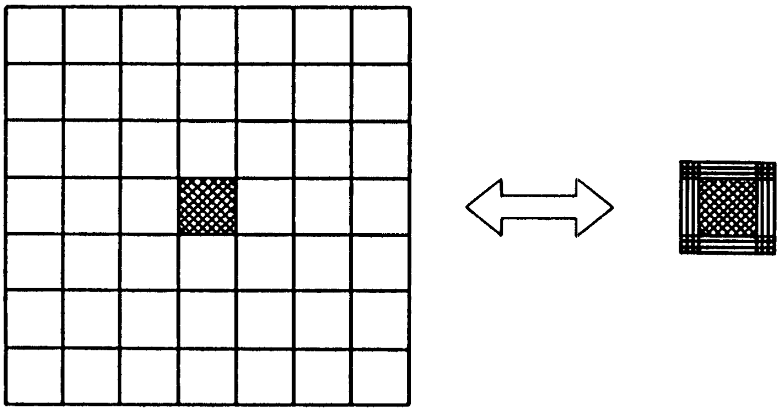

Fig. 18. A Plan View of Deployment/Folding of Space Antenna Composed of SHDF and SHSF Trusses.

The parabolic SHDF/SHSF truss was designed by the same interative numerical calculations as mentioned in Section 4. The RMS of the error for Eq. (1–7) was $6.1\times10^{-6}l$, and that for parabolic shape was $2.0\times10^{-2}l$ when the iteration was terminated. This relatively large errors were due to the application of nesting scheme to the SHSF truss. The scheme was applied to that the SHSF truss was compatible with SHDF truss. Because the global cross-sections of SHSF had to be rectangular when the scheme was applied, the application of the scheme resulted in additional constrains in the design, increasing the shape error. Although the accuracy of the overall parabolic surface of this SHDF/SHSF truss was not so high as that of parabolic SHDF truss, it would not cause serious difficulty in the practical application because

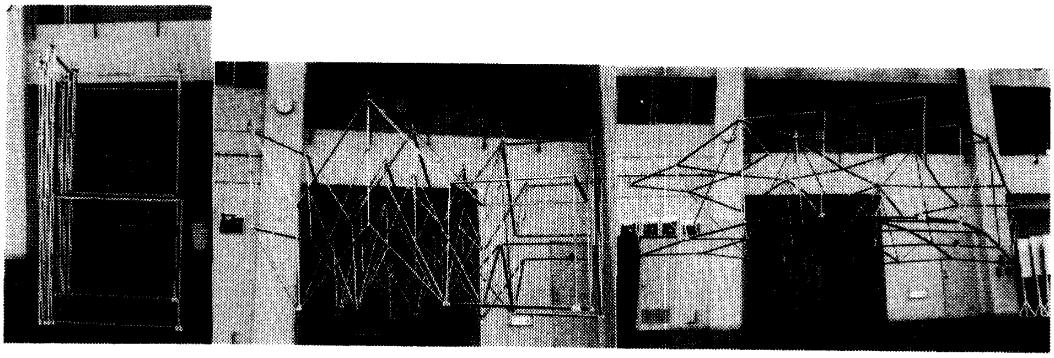

Fig. 19. Deployment/Folding Test of a Parabolic SHDF/SHSF Truss.

small stand-off structure at each nodal point can adjust the shape of the reflector mesh.

All the edge-members in the concave surface were 0.826m in node-to-node length. The length of each member of the reformed model was designed so that it did not exceed the original length since it was a reformed version of the flat model. Neither hinge-assemblies nor actuation devices were reformed.

7.2 Test

Deployment/folding tests of the parabolic model were conducted in a similar way as that of the flat model. Figure 19 shows the model being tested. Just as in the case of the flat model, the tests demonstrated substantially synchronized smooth motions and the practicality of the parabolic SHDF and SHDF/SHSF truss.

8. Concluding Remarks

A new two-dimensionally deployable truss, named Sliding Hinge Double Fold (SHDF) truss, has been briefly described. The SHDF truss can be deployed/folede by the actuation and locking/releasing of a very small number of mechanisms, still having good packaging efficiency and sufficient design flexibility for practical use. A flat functional model was fabricated, and after the deployment/folding tests, it was reformed into a parabolic configuration and combined with a one-dimensionally deployable SHSF truss. Further deployment/folding tests of the parabolic model, as well as those of flat model, demonstrated the kinematic consistency and practicality of SHDF and SHDF/SHSF truss.

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