FABRICATION METHODS FOR LARGE SPACE STRUCTURES

Richard L. Kline
Grumman Aerospace Corporation
Bethpage, New York 11714

Abstract

Space fabrication has a major impact on the development of ultra large space structures. The structural design and materials selection are significantly affected by automatic space fabrication, assembly and orbital transfer of major structural elements as well as by the mission operations in orbit. Development of an automatic facility used to fabricate a structural building block element is reviewed and its application in the construction of larger assemblies examined. Problems related to the construction and operation of large space structures are presented. Structural verification and quality assurance techniques are some of the many technology issues which require further definition; these are explored for possible solutions. The long service life requirement expected for large structures makes their maintenance and refurbishment a key economic issue; methods of repair and replacement of components are reviewed.

Introduction

Many future space programs under active study involve developing, deploying and operating very large satellites in low and geosynchronous orbits. These future systems are exemplified by Space Solar Power Stations, Public Service Platforms, Earth Resources Radiometers, Radio Astronomy Platforms, Microwave Power Transmission Antennas in addition to many other spacecraft. The design, fabrication and assembly of these large area low density structures represents one of the key technological developments needed for the evolution of future spacecraft whose dimensions and weights are very large relative to the launch vehicle delivery capability. The interrelated structural development/construction/assembly problems become evident if one considers the Space Solar Power Station. This satellite concept projects the delivery of unlimited, available power to the public at competetive costs and without the environmental pollution problems encountered in currently used energy sources. The solar radiant energy is collected and concentrated on the solar cells at geosynchronous orbit shown in one illustrative concept, References 1, 2 and 3, converted to microwave energy, transmitted to ground antenna and converted to electrical power for public distribution.

This paper discusses the salient features of space manufacturing including the necessity of demonstrating fabrication and assembly techniques as functions of degree of automation and man's productivity in space. The selection of materials and development of a beam builder module are included together with some potential problem areas. The use of a neutral buoyancy facility to provide early test data is presented. Applications to various large spacecraft are included.

Discussion

Requirement for Fabrication in Space

Space fabrication presents the most attractive approach to placing ultra-large structures into orbit. The planar area and weight requirements for the Solar Power Station (SPS) structure, approximately 64 km^2 and 3×10^6 kg, cannot be produced in orbit by an erectable structural system at acceptable transportation costs. Basic materials of construction can be packaged with significantly higher density in the transport vehicle than with comparable deployable systems.

Our approach to space fabrication is based on using a beam builder module to construct a basic building block structure which can, in turn, be constructed into larger assemblies. Figure 1 shows several categories of candidate large space structures and illustrates a time-phased development plan for Space Solar Power which permits resolution of the key technology issues in discrete, achievable stages. It includes early Solar Power Development Articles (SPDA) up to the full size Solar Power Station. In early phases of the projected program, a one-meter-deep beam is considered as the building block component for the SPDA satellites. The beam builder for a one-meter size building block fits comfortably within the Space Shuttle Orbiter payload bay volume and weight constraints. This makes possible early developmental flights using the Shuttle in a Sortie Mission mode. For a full size SPS, the building block, if necessary, can be scaled up to a larger size. Application of the building block to the other large space structures in the early time period will be based on the specific application.

Fabrication/Assembly - Degree of Automation

The degree of automation and man's involvement is shown in Figure 2. The first graph shows qualitatively the cost per unit structural weight versus the degree of automated assembly for one-of-a-kind space vehicle construction which would be representative of mid-1980's Shuttle-supported space construction activity. When the automation level is increased, cost for man's participation decreases finally to that needed as a maintenance function. As may be expected, the construction system amortization cost increases for higher levels of automation of the overall manufacturing system. The second graph in the figure shows similar trends except that amortization costs are lower because of the larger number of similar units being produced.

At this point in the state of development of space fabrication and assembly there is a clearly defined necessity to start demonstrating the degree of man's involvement in assembly of the structure manufactured by the beam builder module. What are the capabilities and limitations of the building block

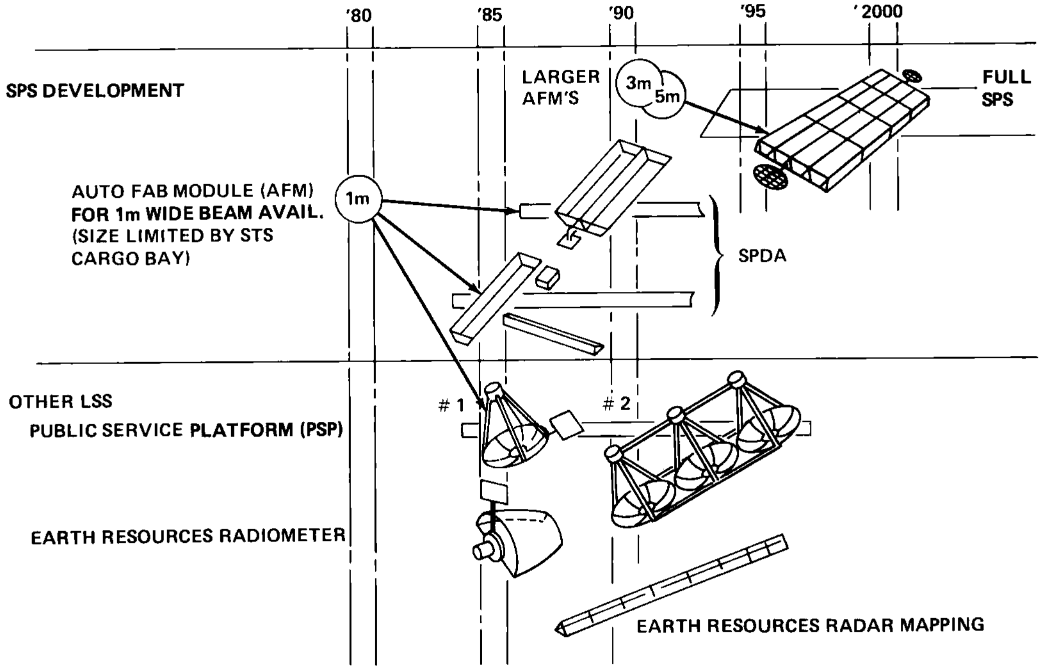
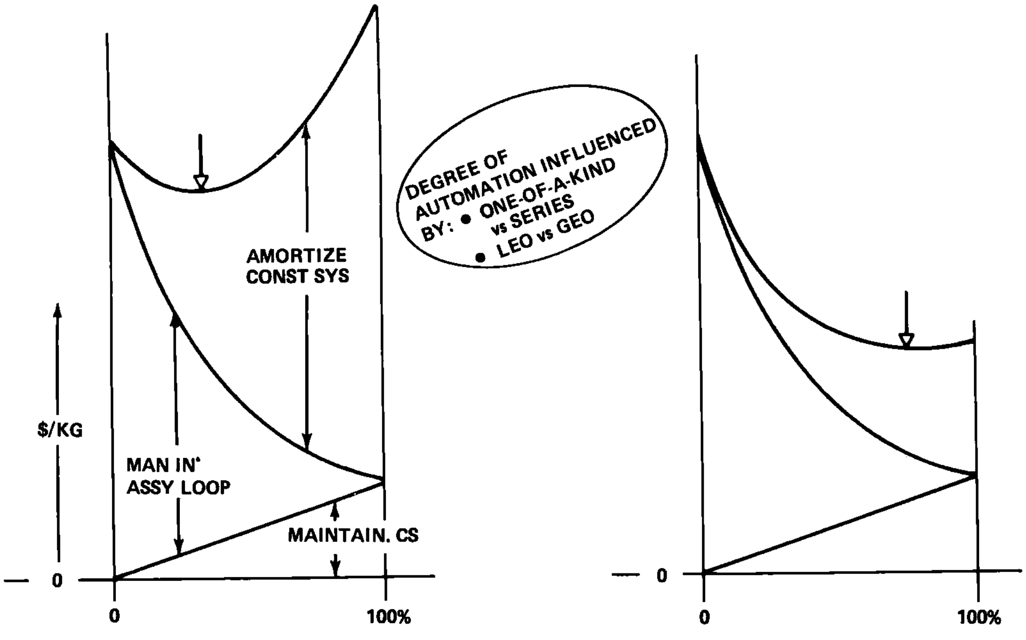


Fig. 1 Candidate Large Space Structure (LSS)



MID '80s CONSTRUCTION, ONE-OF-A-KIND PRODUCTION

SPS SIZE CONSTRUCTION, MASS PRODUCTION

Fig. 2 Construction System - Optimum Degree of Automation

approach and the beam builder module? Can man's output capability keep pace with the required overall productivity? How much assembly will be performed in low earth orbit, how much in geosynchronous orbit or other locations? By getting quantitative data in these areas we can then address the fundamental issue: What level of automation is needed to assemble structures?

Design study and ground experimentation can determine some of the boundaries to this important issue and lead to an efficient shuttle developmental flight program.

The following sections of this paper outline some of the issues which must be settled in order to place Figure 2 on a quantitative basis:

- Basic Structural Building Block
- Beam Builder Module
- Materials and Processes

- Assembly Simulation
- Quality Assurance
- Workbench.

Basic Structural Building Block

Our SPS structural design concept is based on use of a one-meter-deep beam building block. The beam, which is automatically fabricated, is assembled into larger components which can be constructed into an entire structure through the use of a factory in space. The building block concept has a potentially broad spectrum of application as shown in Figure 3.

Figure 4 shows the one-meter beam which will be fabricated in space. The initial concept, designed to SPS conditions, is based on use of 2024-T3 aluminum alloy sheet with a thickness of 0.015 inches. The building block is also designed in composite materials. The material is roll formed into structural shapes and attached at the intersection of the cap members and cross braces. The tripod end attachment is deployable and is attached to the cap members as the beam emerges from the fabricator. The fitting at the apex which connects into the next member will permit assembly even though some initial misalignment is present whether due to built-in imperfections or due to thermal gradients.

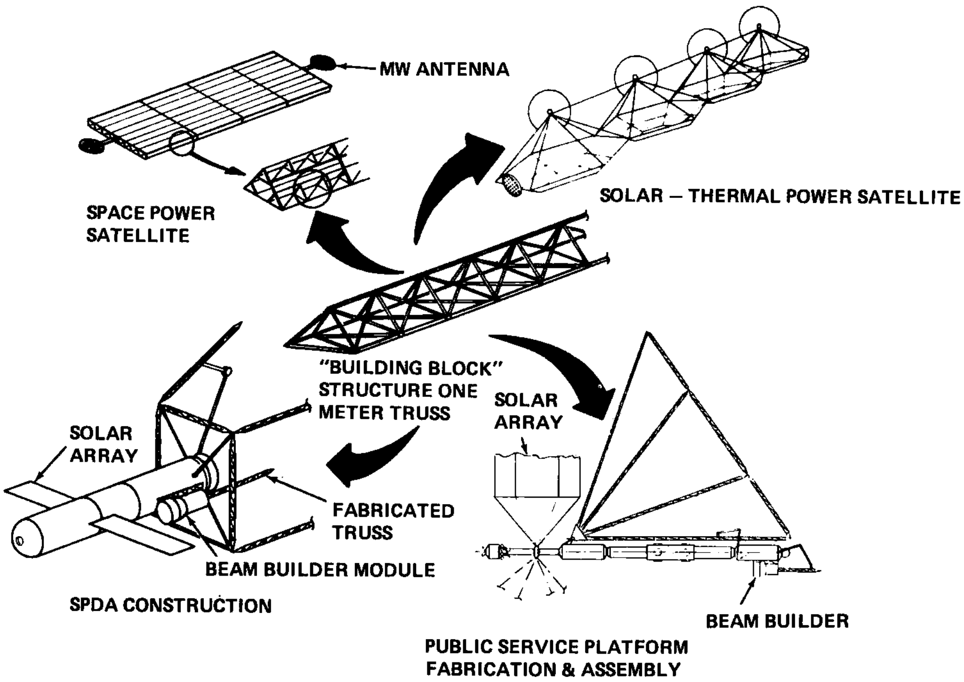


Fig. 3 "Building Block" Structure Applications

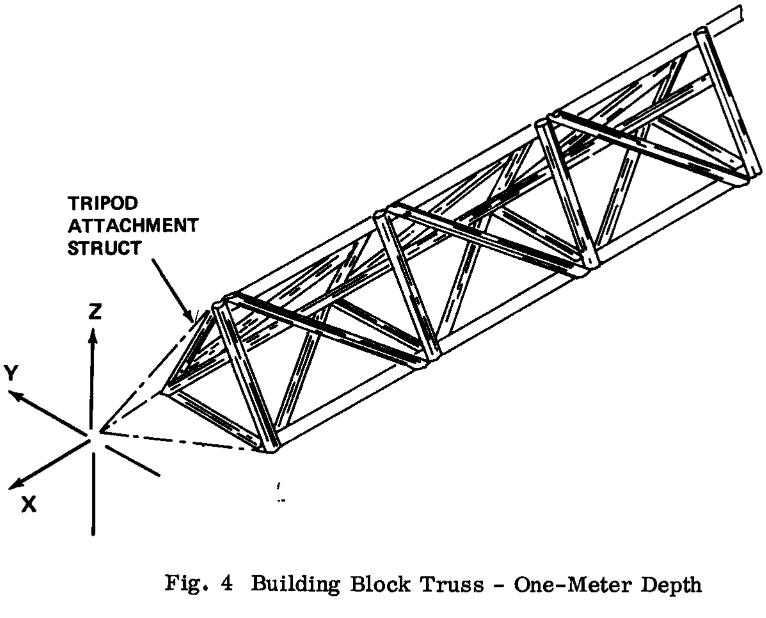
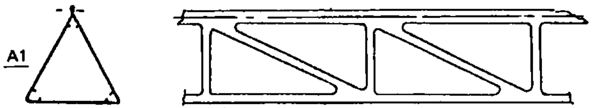


Fig. 4 Building Block Truss - One-Meter Depth

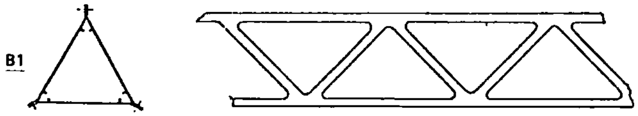
Figure 5 summarizes some automatic fabrication concepts which have been considered for manufacturing both aluminum and composite structures in space. These concepts were developed under the NASA/MSFC contract of Reference 4. Fabrication module designs were analyzed for size, weight, power required, ease of fabrication, end attachment feasibility and structural integrity for the structural design conditions. Concepts A, B, D and E have low stiffness at the cap-stiffener intersection since the stiffener flange does not extend over the cap. Also the cap is not supported in three axes at every cap/stiffener node. Concept C is difficult to fabricate with the required strap preload.

Concept F2 was selected since it can satisfy strength requirements, can readily be fabricated in either composite or aluminum and the processing requirements are not complex.

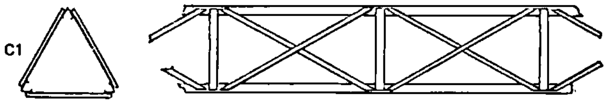
Figure 6 shows the design features and installation of F2 in the orbiter payload bay. The concept consists of roll forming aluminum 2024-T3 for the three caps as well as the diagonal and vertical stiffeners from sheet strips carried in cassettes on the beam builder module. The ground processed material is fed into the six roll forming mills, three for the caps and three for the shear members. The shear members are cut to proper dimension by a guillotine cutter, positioned by the brace alignment mechanism and spot welded to each cap. The one meter building block structure is cut to length as it emerges from the fabrication module.



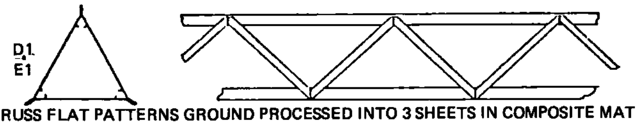
- TRUSS PATTERN GROUND PROCESSED INTO SINGLE FLAT SHEET
- MODULE ROLL FORMS TRIANGULAR SECTION INCLUDING FLANGES & JOINS MEMBER AT APEX
- CONCEPT RESULTED IN UNACCEPTABLY SIZED MODULE; NOT STUDIED FURTHER
- MATERIAL: 2219-T62, 2024-T3, 6061-T6



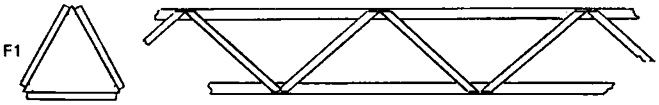
- TRUSS PATTERN GROUND PROCESSED INTO 3 FLAT SHEETS
- MODULE ROLL FORMS 3 SEPARATE SHEETS WHICH ARE JOINED AT APEX
- MATERIAL: 2219-T62, 2024-T3, 6061-T6



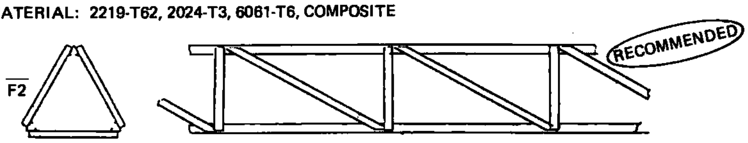
- MODULE ROLL FORMS 3 SEPARATE CAPS & STIFFNERS FROM ALUMINUM STRIP ROLLS
- TRIANGULAR TRUSS FORMED WITH PRELOADED CROSS BRACES, STIFFENERS & BRACE CUT: JOINED AT INTERSECTIONS
- MATERIAL: 2219-T62, 2024-T3, 6061-T6



- TRUSS FLAT PATTERNS GROUND PROCESSED INTO 3 SHEETS IN COMPOSITE MATERIAL
- LAMINATES IN EACH STRIP ORIENTED IN 0° & ±45°
- FLAT PATTERNS ARE ROLL FORMED & FASTENED AT APEXES
- MATERIAL: GRAPHITE/POLYETHERSULFONE OR GRAPHITE/EPOXY



- MODULE ROLL FORMS 3 SEPARATE CAPS AND DIAGONAL STIFFENERS FROM STRIP ALUMINUM ROLLS
- TRIANGULAR TRUSS FORMED BY TRANSFER ARM POSITIONING DIAGONALS AND SPOT WELDED TO CAPS
- MATERIAL: 2219-T62, 2024-T3, 6061-T6, COMPOSITE



- MODULE SIMILAR TO CONFIGURATION F1 EXCEPT THAT STIFFENERS ARE DIFFERENT, CUT TO DIFFERENT LENGTHS BEFORE SPOT WELDING
- THIS CONFIGURATION PROVIDES SIMPLER END ATTACHMENT ALSO GIVES STIFFER SUPPORT AT NODES.
- MATERIAL: 2219-T62, 2024-T3, 6061-T6, GRAPHITE/POLYETHERSULFONE

Fig. 5 Automatic Fabrication Concepts

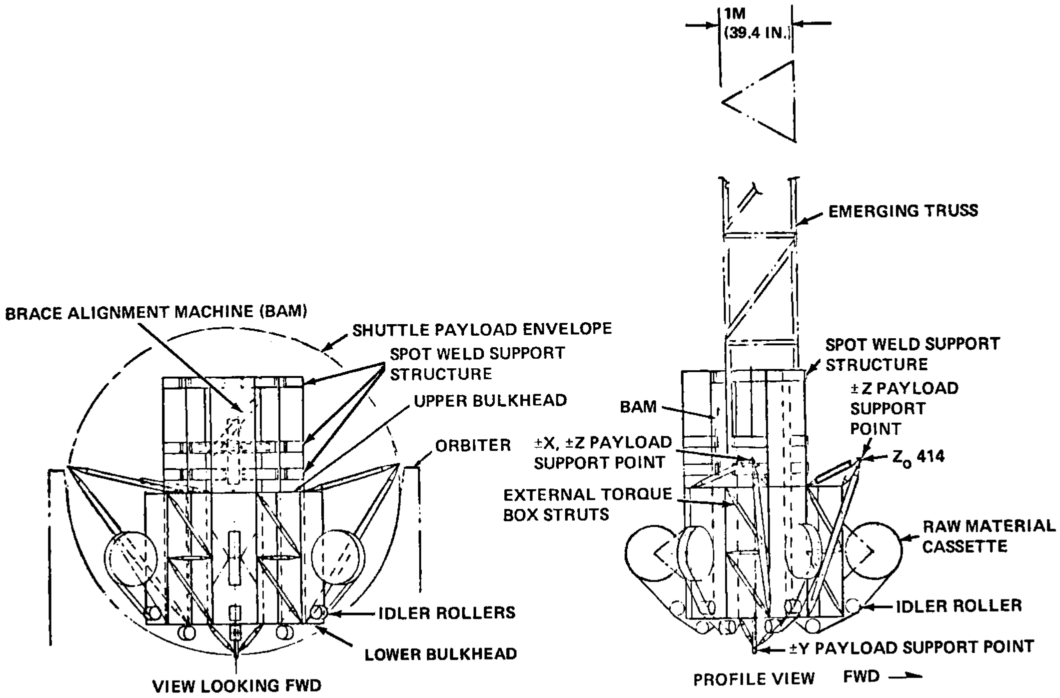


Fig. 6 Beam Builder Module

The design selected for construction in a ground demonstration module which Grumman is building under contract to NASA/MSFC, Reference 5, is shown in Figure 7. It incorporates most of the features of the concept shown in Figure 6 except that the vertical and diagonal members are prefabricated to size, stored in magazines, positioned and attached to the roll formed caps. For very large structure fabrication, it will probably be more efficient to evolve concepts such as shown in Figure 6 which produces the shear brace members in space.

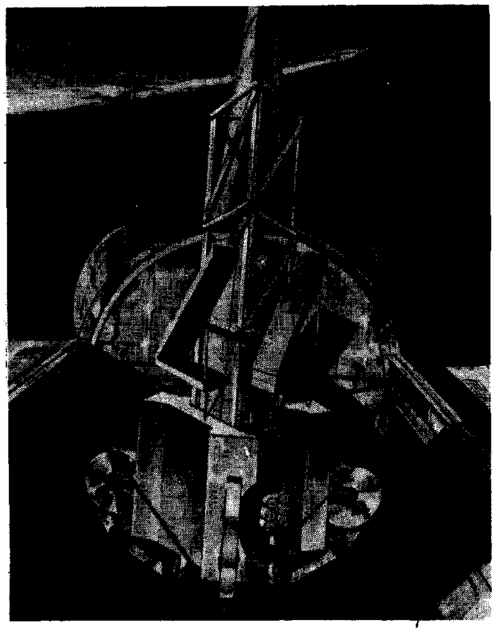


Fig. 7 Beam Builder Concept

A key consideration in the beam building design is its ability to fabricate acceptably straight members. Close synchronization is required between cap forming and the attachment of shear braces. Figure 8 illustrates the problem. In this case the assumption is made that a constant cap exit error occurs during manufacture; the resulting curves show the deflection at the center and the slopes at the ends of a 40-m long

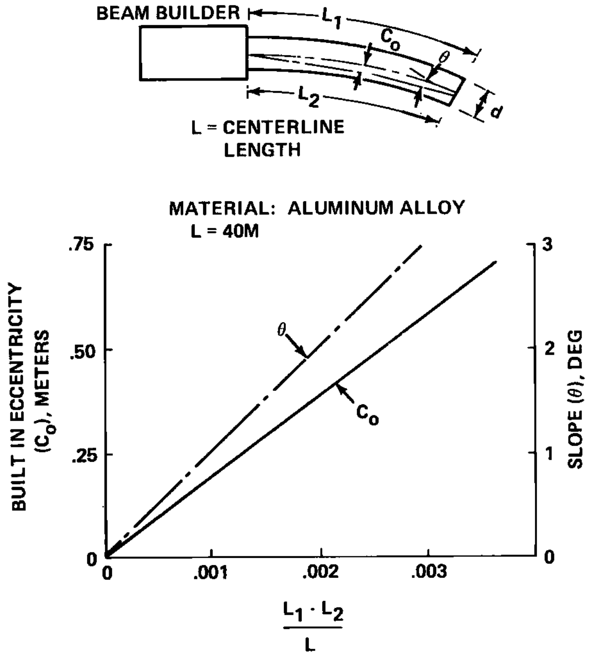


Fig. 8 Deflection and Slope vs Difference in Cap Lengths

building block beam. The significance of the deflection is apparent when design compressive end loads are applied to the member, in addition the slopes and possible foreshortening present potential problems to the end attachment design. Design concepts and laboratory tests are underway to accurately measure the position of each cap as the roll-forming process develops, process the data, and zero out any error in each succeeding 1-1/2 m bay length. The process control system currently being developed should avoid accumulated errors and thus construct beams within acceptable tolerances.

It can be seen in Figure 9 that the thermal deformation of the beam at the center may be additive to fabrication rate imperfections depending on the orientation and the resulting temperature differential. The deflections and slopes of the 1 m by 40 m beam constructed from aluminum alloy are presented in the figure as a function of thermal gradients between cap members. Thermal studies have shown that for worst-case orientation of the 1 m by 40 m beam with an α/ϵ of .86/.83 for anodized aluminum, the value of ΔT is approximately 40°F which results in a centerline deflection of about four inches. An advantage of the composite structure is that deflection can be very much less for the same temperature differential.

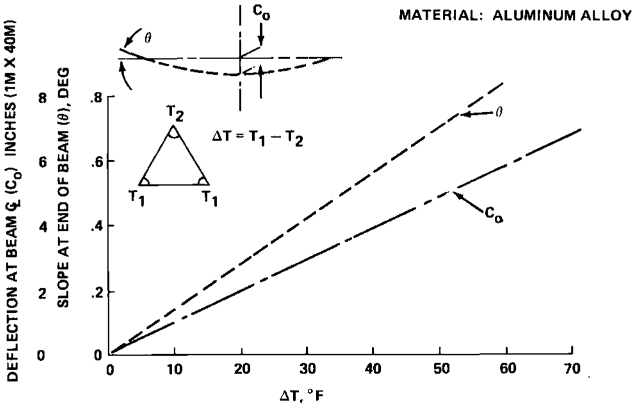


Fig. 9 Deflection and Slope vs Temperature Differential for 1 x 40 Meter Beams

Materials and Processes

Table I summarizes several candidate materials evaluated for manufacturing in space. The candidate aluminum alloys were selected because of their relatively high allowable compression yield stresses, in the order of 35 ksi. The alloys are also weldable and have good property retention up to approximately 350° F. These metallics are all capable of being roll formed although the springback on the 2024 alloy is less than the others. The bend radius is 10t which for our selected gage of 0.015 inches does not present a roll-forming problem. Initial development of the fabrication module is based on using series resistance spot welding. Other possible attachment methods are: electron beam welding, laser welding, ultrasonic welding, and non-debris-forming mechanical fasteners.

The thermoset and thermoplastic composite materials, Graphite/Epoxy and Graphite/Polyethersulfone respectively, References 7 and 8, are both prime candidates for automatic space fabrication.

Table 1 Material Comparison

MATERIALS	ALUMINUM* 2219-T6	GRAPHITE/EPOXY $(0_2 \pm 45_2)$	GRAPHITE/POLYETHER - SULFONE $[0_2 \pm 45_2]$·
F_{TU}, KSI	54	69	69
F_{TY}, KSI	36	--	--
F_{CY}, KSI	38	66	66
E, KSI	10.5×10^3	7.7×10^3	7.7×10^3
ρ, LB/IN.^{3}	.103	.055	.058
α, IN./IN./°F	12.4×10^{-6}	$.1 \times 10^{-6}$	$.1 \times 10^{-6}$
TEMP LIMIT, °F	350	350	440
HANDLING QUALITY DURING FAB	GOOD	● MUST BE "C" STAGE ● PARTIALLY FORMED	GOOD
THERMAL COATING	FAIR APPLY COATING TO BASIC MATERIAL IN GRD PROCESS, MUST BE REMOVED FOR JOINING	EXCELLENT INCORPORATED INTO RESIN MATERIAL DURING PROCESSING GROUND	EXCELLENT INCORPORATED INTO RESIN MATERIAL DURING PROCESSING GROUND
JOINING	EXCELLENT CAN USE ANY OF THE FOLLOWING: ULTRASONIC WELD, PRESSURE WELD, MECHANICAL ATTACHMENT	POOR BONDING REQUIRES MELT & CURE	VERY GOOD ULTRASONIC WELD GIVES GOOD SIMPLE ATTACHMENT
UV DEGRADATION	EXCELLENT	NOT KNOWN	NOT KNOWN
STATE-OF-THE-ART OF APPLICATION	EXCELLENT	GOOD	NOT KNOWN
* PROPERTIES OF 2024-T3 and 6061-T6 APPROXIMATELY THE SAME			

The significant characteristics compared to aluminum are the stiffness and strength-to-density ratios and particularly the low coefficients of thermal expansion. The composite designed structure will be lighter and result in lower thermal distortions and stresses caused by thermal gradients, since these are functions of $\alpha \Delta T$ and $E\alpha\Delta T$ respectively. The graphite thermoplastic strip lay up will be preheated, formed in preheated forming rolls, cured and attached to shear braces. The effect of ultraviolet and other forms of radiation exposure on the composites over long service life at geosynchronous orbit must be investigated. Outgassing may also present a problem on degradation of solar cell efficiency.

Assembly Simulation

While space manufacture of beams is the first step in the overall construction process, the techniques of combining these structures into the next assembly must be developed and demonstrated with consideration given to the degree of automation, Figure 10.

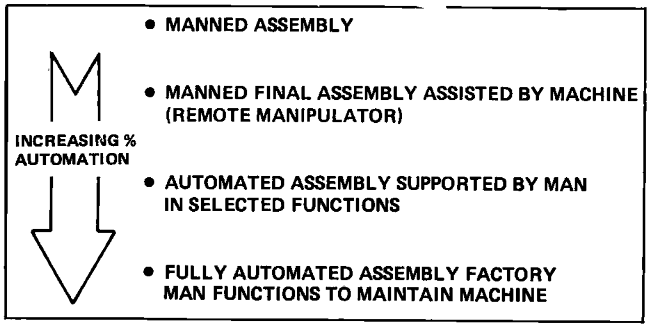


Fig. 10 Space Fabrication of Large Structures Assembly Mode Options

In the early development stages of large space structures fabrication, assembly options may include assembling beams using man only or man assisted by remote manipulator. The next assembly modes would consist of an automated assembly system with man's role limited to certain key functions such as rigging preloaded tension cable systems in very large assemblies. Finally, a fully automatic factory option will exhibit the highest productivity - assuming the entire system has been debugged and is in serial operation. Man's role in this operation will consist of maintaining, refurbishing and resupplying the factory.

Reference 6 presents the data and results of simulation tests carried out in the Neutral Buoyancy Facility, Figure 11, at NASA/Marshall Space Flight Center to demonstrate the man-machine role in space manufacturing. The purpose of the simulation was to compare the first two options of Figure 10; the modes were man and man with remote manipulator with the man performing the final assembly process.

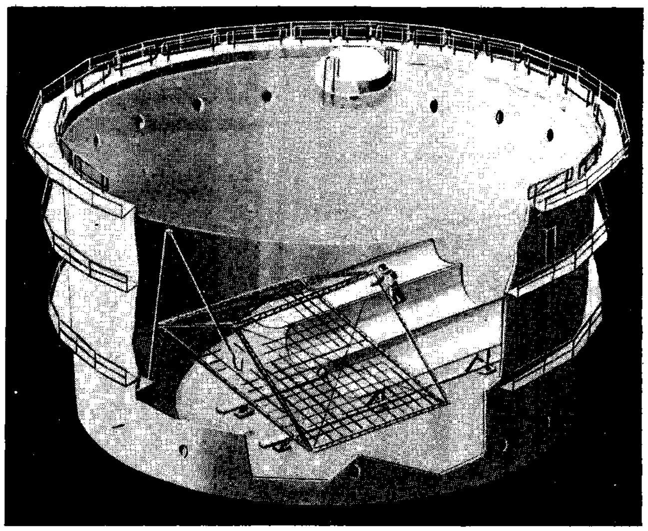


Fig. 11 Assembly Simulation in N.B. Tank

Three lightweight structural beams made of 6061-T6 aluminum were used, Figure 12. Each beam was 20-ft long and measured 2-ft from the apex of the cross section to the opposite plane. Stanchions provided support to the beams when the beam structure was positioned over the simulated shuttle cargo bay.

As reported in Reference 6, the test was generally a success. The rate of travel was slow enough to negate water drag. Several hardware-peculiar problems affected test subject performance which contributed to making the assembly task more difficult than expected initially.

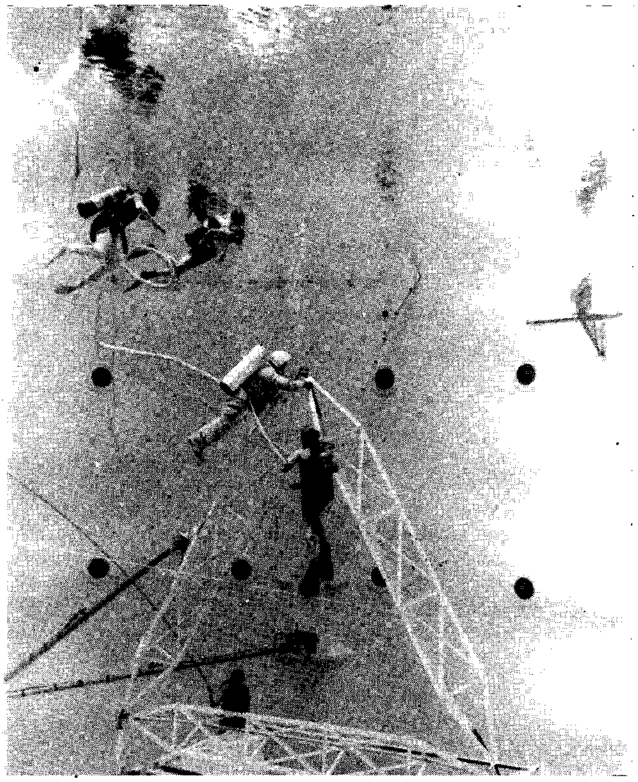


Fig. 12 Men in N.B. Tank

However, the objectives of the study were effectively met. The test as performed demonstrated that the positioning task is greatly enhanced by using the manipulator to position a beam to be manually joined with another beam. The assembly task in the "man-only" mode physically stressed the test subject.

Fig. 13 Man Assembling in NB Tank

The design of the joint structure played a significant role in the level of effort expended by the man in the test. The hole/rod concept with the inherently close tolerance requirements and the use of similar materials for fitting and rod, Figure 13, reduced man's productivity. What is needed is a simple, easy, quick attachment joint, which permits some degree of misalignment during joining, and locks into the proper structural configuration. Man's productivity is strongly influenced by good detail design. Figure 14

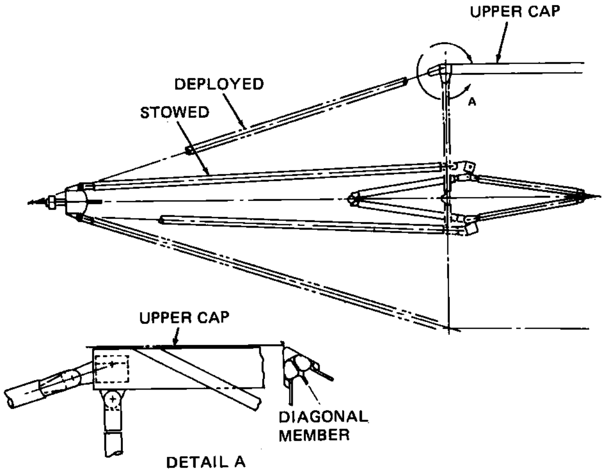


Fig. 14 Foldable Tripod End Attachment for One-Meter Truss

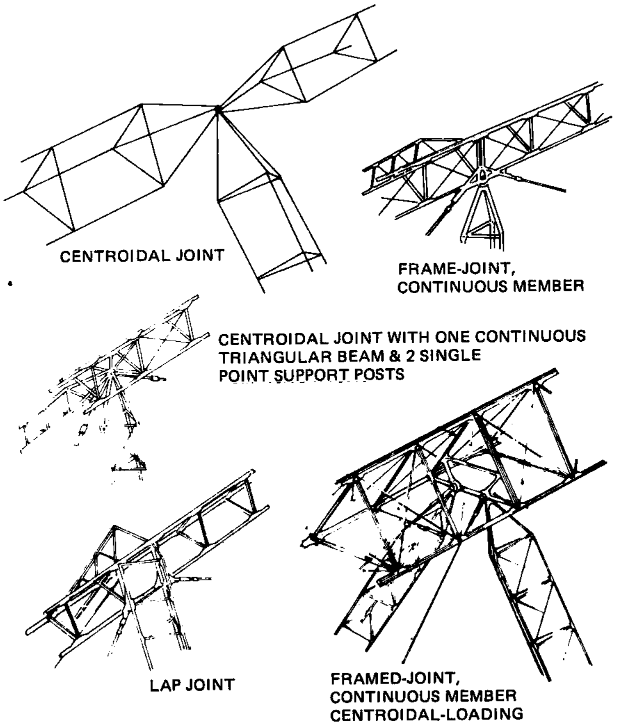


Fig. 15 End-Attachment Concepts