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Potential for On-Orbit Manufacture of Large Space Structures Using the Pultrusion Process

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Abstract

On-orbit manufacture of lightweight, high-strength, advanced-composite structures using the pultrusion process is proposed. This process is adaptable to a zero-gravity environment by using preimpregnated graphite-fiber reinforcement systems. The reinforcement material is preimpregnated with a high-performance thermoplastic resin at a ground station, is coiled on spools for compact storage, and is transported into Earth-orbit. A pultrusion machine is installed in the Shuttle cargo bay from which very long lengths of the desired structure are fabricated on-orbit. Potential structural profiles include rods, angles, channels, hat sections, tubes, honeycomb-cored panels, and T, H, and I beams. By manufacturing structures on-orbit in continuous lengths, the number of joints would be greatly reduced compared with structures manufactured at a ground station and assembled in space. Horizontal members are joined to vertical members by ultrasonic or conductive welding techniques. In this way, the structural materials can be transported to orbit at high packaging density for fabrication of very-low-density structure on-orbit. Tailored properties such as stiffness, tensile strength, and toughness are controlled by precise fiber orientations and selective combinations of matrix and fiber systems. Illustrations describing the pultruder and its arrangement in the Shuttle bay are presented. Properties of thermoplastic/graphite structures fabricated on-orbit are projected using pultrusion. This fabrication method has the potential for on-orbit manufacture of structural members for space platforms, large space antennas, and long tethers.

Introduction

The potential for on-orbit manufacture of large space structures using the pultrusion method is greatly enhanced by the development of high-temperature, high-strength thermoplastic polymers containing continuous graphite-fiber reinforcement. These composites are 35 percent lighter than aluminum alloys, and their strength values can be tailored to exceed those of conventional aluminum alloys by magnitudes of two to three. (See ref. 1.) At the present time, two such high-performance thermoplastic composites are commercially available in preimpregnated form: polyetheretherketone (PEEK) as Victrex[1] PEEK carbon fiber and polyphenylene sulfide (PPS) as Ryton[2] carbon. These composites, as well as a large selection of other thermoplastic resins, have characteristics which would be advantageous to on-orbit manufacture of long, lightweight structures. Several potential candidates for pultrusion and post-forming development and a comparison of some of their physical and mechanical properties are shown in table I. In the table, ULTEM[3] 6000 and ULTEM 1000, polyetherimides (PEI), and Torlon[4], polyamide-imide (PAI) are amorphous; Victrex (PEEK) is crystalline in structure; and XYDAR[5] is a liquid crystalline polymer (LCP). The table shows that Torlon has the highest tensile and flexural strength values and is slightly higher in specific gravity, but XYDAR has the highest heat resistance capability. Other desirable characteristics of these thermoplastics are their high solvent resistance, damage tolerance, and compressive strength. In addition to their potential for joining by welding and for post-forming by applying heat and pressure, these materials are likely candidates for on-orbit manufacturing. For example, coiled stock, having a solventless thermoplastic matrix, could be transferred to space in a very high storage density compared with that of finished structures. The coiled stock could then be post-fabricated into specific shapes by methods similar to those used in post-forming conventional metals such as aluminum and titanium alloys. In using solventless thermoplastic/graphite prepreg, toxic fumes would be eliminated during the on-orbit fabrication phase. (See ref. 2.) One of the purposes of this paper is to present a method for manufacturing large space structures on-orbit. In concept, coiled stock, with a very high storage density during transport, would be fabricated into very-low-density large space structures. Some of the concepts in the paper have not been developed and require a considerable amount of additional research and development; some concepts are presently being developed.

Proposed Manufacturing Method

The proposed manufacturing method consists of two phases. The first phase requires manufacturing and coiling stock material at a ground base using a pultrusion process. The second phase is on-orbit post-fabrication and is accomplished by rollforming or rolltruding the coiled stock into specific shapes or profiles. The ground-based pultrusion phase produces solventless double-plied prepreg. The prepreg could include communications wiring or this could be added during the on-orbit fabrication. Figure 1 is a schematic of a conventional pultrusion process. A machine designed to perform the functions of the

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[1] Trademark of Imperial Chemical Industries.

[2] Trademark of Phillips Petroleum Company.

[3] Trademark of General Electric Company.

[4] Trademark of Amoco Chemicals Corporation.

[5] Trademark of Dartco Manufacturing, Inc.

pultrusion process is shown in figure 2. Its major functions are to impregnate reinforcement fiber and to subsequently pull the impregnated fiber through a cure die on a continuous basis, thus forming a cured composite structure. The pultrusion fabrication of thermoplastic/graphite coiled stock for on-orbit rolltrusion would require some of the same techniques presently used in conventional pultrusion. For example, multidirectional fiber orientations would be achieved by using two oriented plies stitched together, or knit-locked, to provide the desired fiber directions. This material is shown being impregnated in a conventional solvent resin system in figure 3. A solventless thermoplastic resin/graphite prepreg is proposed for on-orbit manufacture and would require an extruder to inject the polymer into the oriented plies of graphite fiber. A T-beam stiffener is shown emerging from the cure die fully shaped and cured at a rate of 1 ft/min in figure 4. A thermoplastic rolltrusion system would have a potential manufacturing speed of 10 ft/min. The manufacture of continuous long lengths by the conventional method (ref. 3) is shown in figure 5. Pultruded graphite/thermoplastic stock material for on-orbit rolltrusion would be produced in continuous 2-ply knit-locked coiled stock. Figure 6 is a schematic of a potential thermoplastic pultrusion machine. The functions of this machine are to unwind reinforcement fiber, to impregnate the fiber with a hot-melt solventless thermoplastic, and to rewind the material on lightweight composite spools for Earth-to-orbit (ETO) transfer. Upon delivery to orbit, the spools of prepreg are installed on a rolltrusion machine. (See fig. 7.) The machine would consist of a creel from which coiled prepreg stock is pulled into a rollforming or rolltrusion chamber. The chamber would be designed to consolidate, compact, and rollform the material into a specific shape by applying heat and pressure. The formed shape would continue to travel out of the chamber and be sliced to lengths required. This method of fabrication would be capable of producing very long lengths in a weightless environment. Continuous monitoring for delaminations could be performed at the exit end of the rolltrusion chamber by nondestructive acoustic impedance ultrasonic inspection. (See ref. 4.) The machine would require a space of approximately 10 ft in length and 3 ft in width. The height requirement would be dictated by the spool diameters and arrangements. Several of these machines could conceivably be placed inside the Shuttle cargo bay and on-orbit fabrication could be started and extended from such an orbiting vehicle. A concept for the arrangement of three such machines and an assembly robot in a Shuttle cargo bay are shown in figure 8.

Preliminary Materials Evaluation

Pultruded composite structure with a high performance thermoplastic has been reported by only one researcher (ref. 5). The pultrusion of polyphenylene sulfide with reinforcement materials of both fiberglass and graphite fiber was reported in reference 5. Because of the early development stages of pultrusion processes using high-performance thermoplastics, data are not available to evaluate properties of materials produced by this method. However, approximations of some of the mechanical properties can be derived by using equations such as the Halpin-Tsai equations. (See ref. 6.) The equation for the Halpin-Tsai rule of mixtures was used to estimate the probable moduli of graphite-reinforced pultrusions; each of the thermoplastics listed in table II were used as matrices and polyacrylonitrile (PAN)-base graphite fiber (Hercules AS4[6]). The equation form is

$$E_{11} = E_f V_f + E_m V_m$$

where E_{11} is the modulus of the composite, E_f and E_m are the moduli of the graphite reinforcement and matrix, respectively, and V_f and V_m are the volume fractions of the reinforcement and matrix, respectively. The values for tensile moduli and specific tensile moduli are shown in table II. These values are comparable to values reported for graphite/epoxy composite systems using conventional fabrication technology. (See ref. 7.) These values are shown graphically in figure 9 to illustrate that the high-modulus XYDAR caused the only significant increase in tensile properties.

On-Orbit Fabrication of Large Space Structures

A polyetherimide/graphite (Hercules AS4) rolltruded channel structure with a density of 0.057 lb/in^3 is presented as a model for determining the mass properties of a large space structure. The structure would consist of 600 sections welded together to form a structure 300 ft wide by 25 ft high by 5000 ft long. A typical section is shown in figure 10. The structure would require channels of three varied widths to simplify assembly. Figure 11 illustrates the versatility of a channel design. The channels are constant in cross-sectional dimensions, and each would have flange widths of 1.5 in. and wall thicknesses of 0.080 in. The channels have dimensions across the webs of 3.0 in., 2.8 in., and 2.6 in., respectively. Some of the advantages of using channel structure are (1) the ease of rolltruding a simple shape; (2) the

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[6] Trademark of Hercules, Inc.

elimination of mechanical fasteners for assembly; and (3) the versatility of combining channels to form other shapes such as H, T, cross, or closed-box beams for vertical and diagonal stiffeners. The proposed design requires only three varied size channels and provides flat surfaces for attaching modules such as living, storage, and work areas. Structures fabricated from polyetherimide/graphite could be joined by bonding, welding, or mechanical methods.

Several thermoplastic joining techniques have been investigated. (See refs. 8 through 12.) The most promising technique is the "Plastic Welder" (ref. 9), which was developed at Langley Research Center. This technique uses an induction heating toroid gun to produce fusion welds in thermoplastics. The technique could conceivably be modified to use a solar power source for on-orbit use. (See fig. 12.) Figure 13 is an artist's rendition of on-orbit manufacture and construction of a large space platform. The concept envisions a rectangular shape. In the figure, channel structure is being produced by rolltrusion machines located in the three attached modules. By using on-orbit manufacturing, the longitudinal stiffeners could be produced in continuous 5000-ft lengths or longer. A spider crane robot is used for assembling the structure. A compilation of channel lengths, weights, and volumes for ground-based manufacture and on-orbit assembly is shown in table III. The total delivered weight is 106 200 lb, and the volume is 5161 ft^3. The weight and volume compilation for on-orbit manufacture of the same structure using ground-based pultruded coiled stock is shown in table IV. This method of manufacture would require an ETO lift capability of 110 200 lb or an increase of 4000 lb because of the added empty weight of the spools. The storage volume, however, would be reduced by 2900 ft^3. A comparison of ETO delivered densities of ground-based versus on-orbit manufacture of the same structure is given in table V. The delivered density using the on-orbit method is 2.3 times greater than that of the ground-based method. Based on these calculations, the on-orbit-fabricated structure would require only 43.7 percent of the ETO volume required by the ground-based-manufactured structure.

The environmental difficulties involved in space manufacturing and construction are not addressed in this paper; however, many of these problems would be overcome by the use of high-tech robotic assembly. A potential robot assistant, a spider crane, is shown in figure 14. The spider would be operated in a telepresence mode; that is, there would be combined voice commands and computer-program control by an observing astronaut located in a mobile life-support capsule. The spider crane could perform cutting, fitting, and assembly as illustrated in figure 14.

Another potential on-orbit manufacturing concept using the pultrusion method is shown in figure 15. This concept would be suitable for manufacturing large space antennas and solar reflectors. The configuration shown is an Archimedean spiral, and Δr equals the pitch K of the Archimedean spiral. In this concept, a core circle or plate would first be manufactured and used to anchor the radial structure. (See fig. 16.) The robot spider would then be used to rolltrude the radial network. The figure shows parallel construction by using two rolltrusion machines. In this operation, the machines are moving, and the robot is using the structure to walk on as it is being fabricated. The spiral is manufactured in one continuous length, as shown in figure 17. Assuming $\Delta r = 20$ ft, the length of the spiral required would be approximately 3500 ft for a 200-ft-diameter structure and would require 4 spools of 2-ply prepreg wound on 24-in-diameter cores. The outside diameter of the spools would be approximately 46 in. The 4 spools of prepreg could rolltrude an 8-ply structure that is 0.080 in. in wall thickness.

Combinations of pultrusion/rolltrusion technology with potential on-orbit fabrication of specific structure are not limited to any particular design. The unlimited applications of these futuristic high-tech manufacturing methods are illustrated in figure 18.

Concluding Remarks

On-orbit manufacturing concepts for large space structures using lightweight, high-strength, advanced-composite materials and advanced high-tech fabrication methodology are presented. A potential pultrudable thermoplastic/graphite composite material is presented as a model for determining the effect on Earth-to-orbit package density of on-orbit manufacture of large space structures. The results indicate that by using pultruded coiled stock and on-orbit manufacture, the package density is increased by 132 percent and the payload volume requirement is decreased by 56.3 percent. This represents a substantial decrease in payload volume requirements for the transport of structures to orbit.

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Table I. Properties of Potential Pultrusion Thermoplastic Resins

Property	ULTEM 6000 (PEI)	ULTEM 1000 (PEI)	Torlon 4203 (PAI)	Victrex (PEEK)	XYDAR SRT-300 (LCP)
Melt temperature, °F	435	420	528	633	680
Specific gravity	1.27	1.27	1.38	1.32	1.35
Tensile strength, psi	15 000	15 200	27 800	15 000	20 000
Flexural strength, psi	21 000	22 000	34 900	16 000	19 000
Deflection temperature under load, °F at 264 psi	420	392	500-525	320	671
Flexural modulus, psi	440×10^3	480×10^3	$520\text{-}665 \times 10^3$	560×10^3	2000×10^3

Table II. Properties of Potential Thermoplastic/Graphite Pultrusion

Property	ULTEM 6000 (PEI)	ULTEM 1000 (PEI)	Torlon 4203 (PAI)	Victrex (PEEK)	XYDAR SRT-300 (LCP)
Fiber orientation	[0°]	[0°]	[0°]	[0°]	[0°]
Fiber[a] volume, %	60	60	60	60	60
Density, lb/in^3	.058	.058	.059	.058	.059
Tensile modulus,[b] psi	20.6×10^6	20.6×10^6	20.7×10^6	20.6×10^6	21.4×10^6
Specific tensile modulus, psi	355×10^6	355×10^6	351×10^6	349×10^6	362×10^6

[a] Hercules AS4 graphite.
[b] Calculated values based on Halpin-Tsai equation.

Table III. Ground-Based Manufacture of Thermoplastic/Graphite Channel for Space Platform

[300 ft by 25 ft by 5000 ft]

Channel stiffener, in.	Length required, ft	Number of pieces required	Total length, ft	On-board weight, lb	On-board volume, ft^3
1.5 by 3.0 by 1.5					
Horizontal	50.00	1400	70 000	22 500	1123
Horizontal	49.75	1212	60 300	19 400	1019
1.5 by 2.8 by 1.5					
Vertical	24.75	998	24 700	7700	371
Vertical	25.00	1198	30 000	9300	449
1.5 by 2.6 by 1.5					
Diagonal	70.70	1200	84 800	25 500	1184
Diagonal	55.90	1300	72 700	21 800	1015
			Total	106 200	5161

Table IV. On-Orbit Manufacture of Thermoplastic/Graphite Channel for Space Platform Using Ground-Based Fabricated Prepreg

[300 ft by 25 ft by 5000 ft]

Prepreg width, in.	Length, ft	Spools required	On-board weight, lb		Storage volume, ft^3
			Prepreg	Spools	
5.84 (for 3-in. channel)	521 000	102	41 900	1400	891
5.64 (for 2.8-in. channel)	220 000	43	17 100	0600	362
5.44 (for 2.6-in. channel)	632 000	124	47 300	1700	1005
		Total	110 200		2258

Table V. Comparison of Earth-To-Orbit Storage Densities of Ground-Based Versus On-Orbit Manufacture of Space Platform Using Pultrusion/Rolltrusion Method

[300 ft by 25 ft by 5000 ft]

Channel stiffener, in.	Total length, ft	Ground-based-manufactured delivered density, lb/ft^3	On-orbit-manufactured delivered density, lb/ft^3
1.5 by 3.0 by 1.5	130 300	19.6	48.7
Vertical stiffness 1.5 by 2.8 by 1.5	55 000	21.0	48.9
Diagonal stiffness 1.5 by 2.6 by 1.5	158 000	22.3	48.9
	Average	21.0	48.8

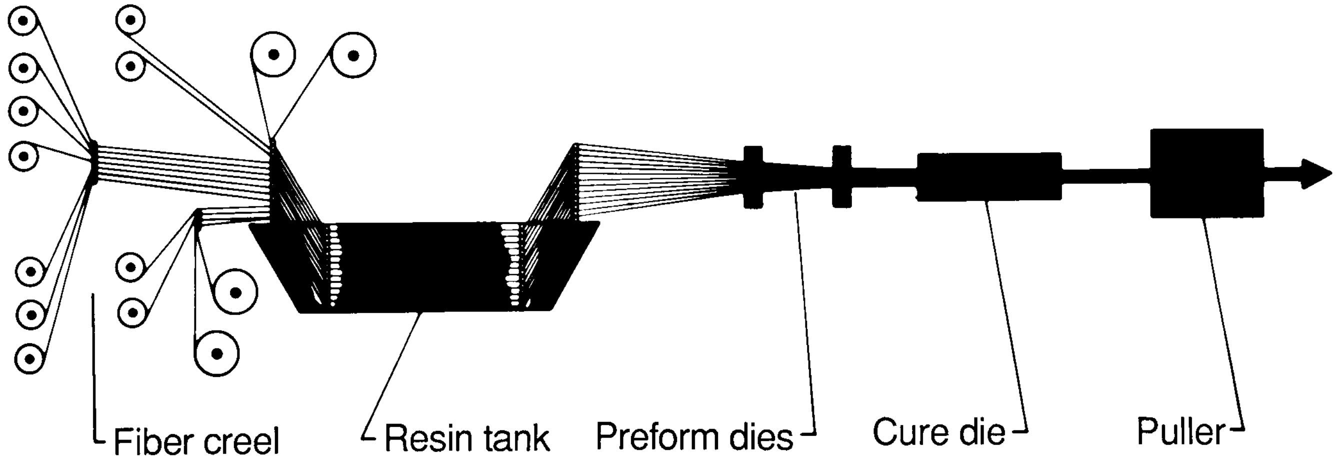

Figure 1. Schematic of pultrusion process.

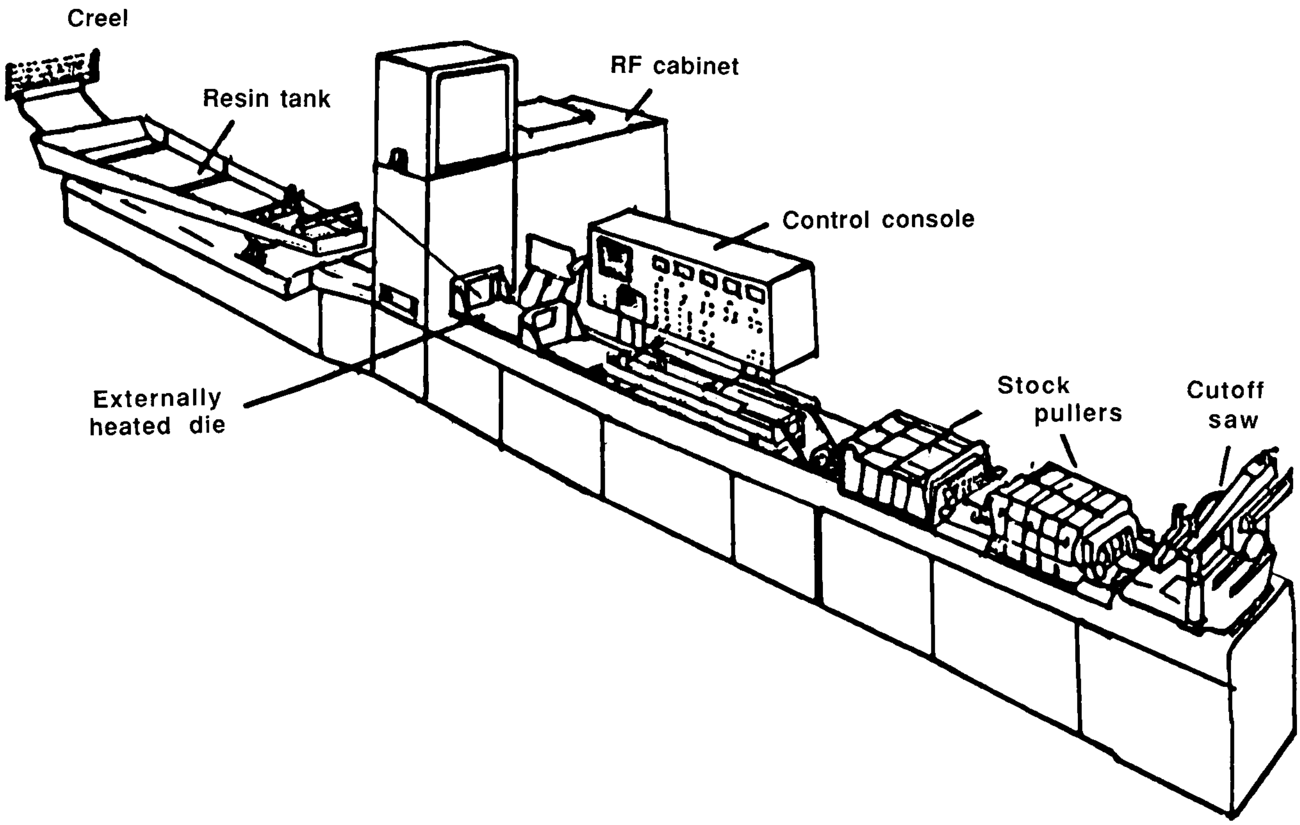

Figure 2. Pultrusion machine.

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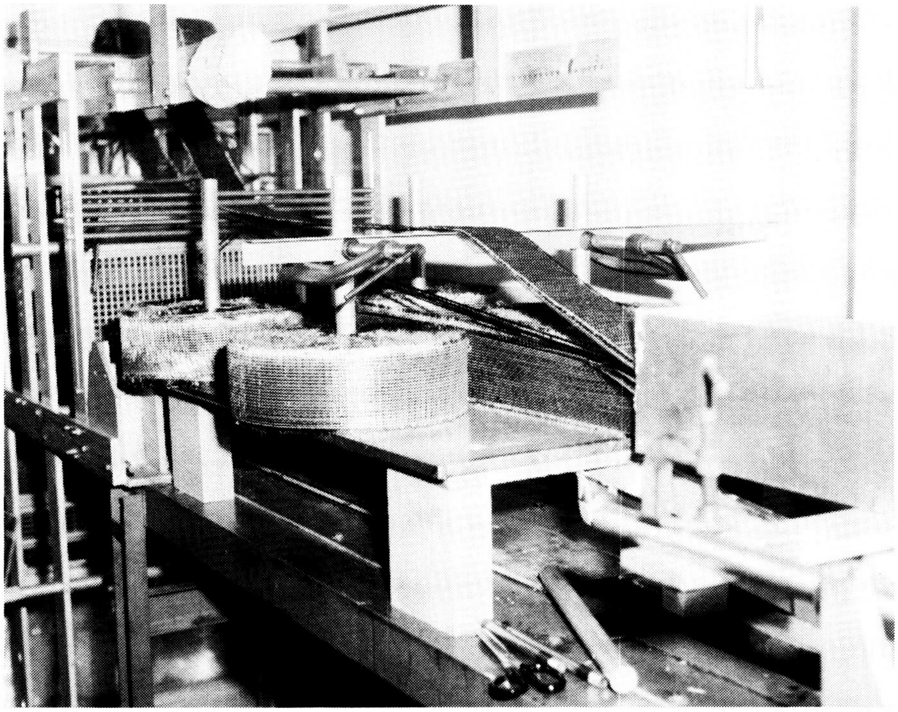

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Figure 3. Multidirectional fiber creel.

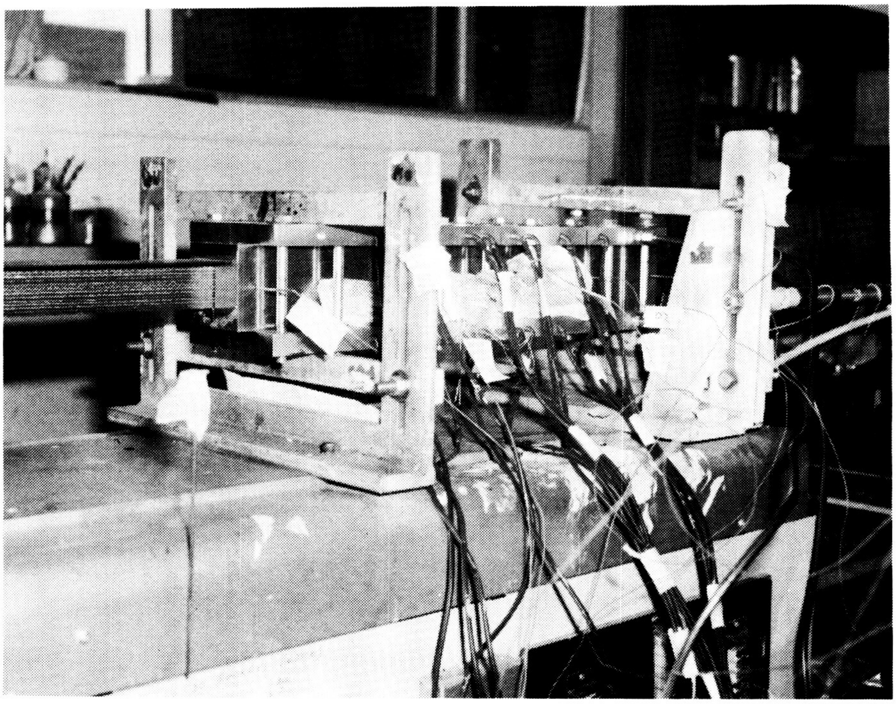

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Figure 4. Pultruding T-beam.

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Figure 5. Continuous-length pultrusion.

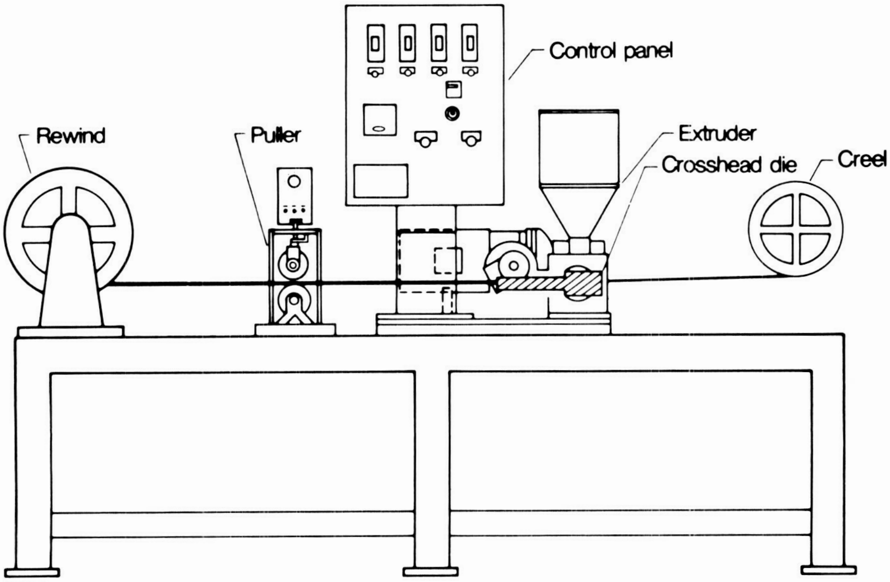

Figure 6. Thermoplastic pultrusion.

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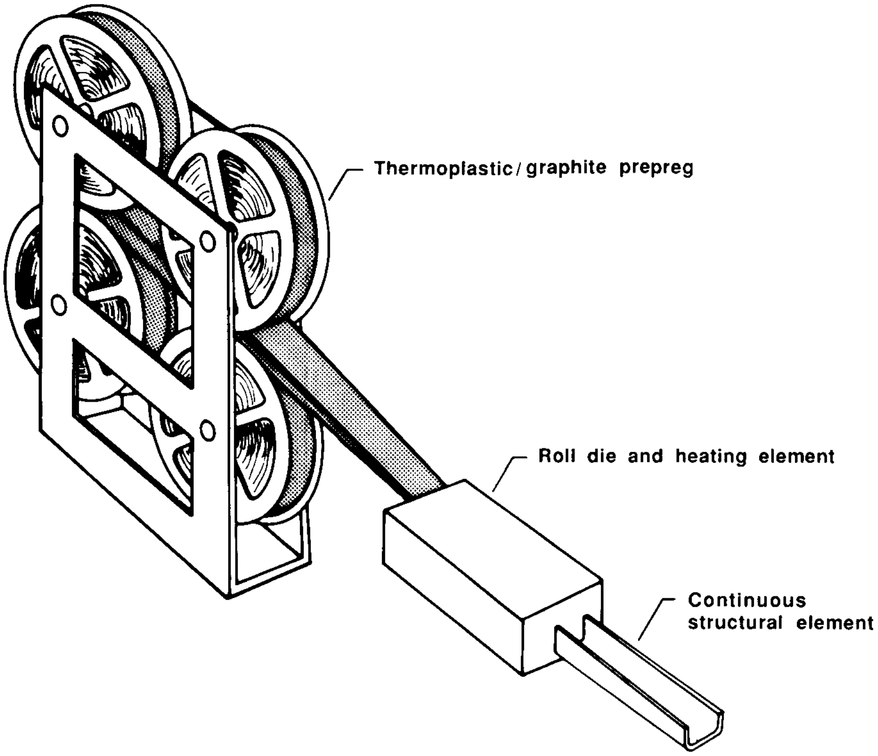

Figure 7. Thermoplastic rolltrusion.

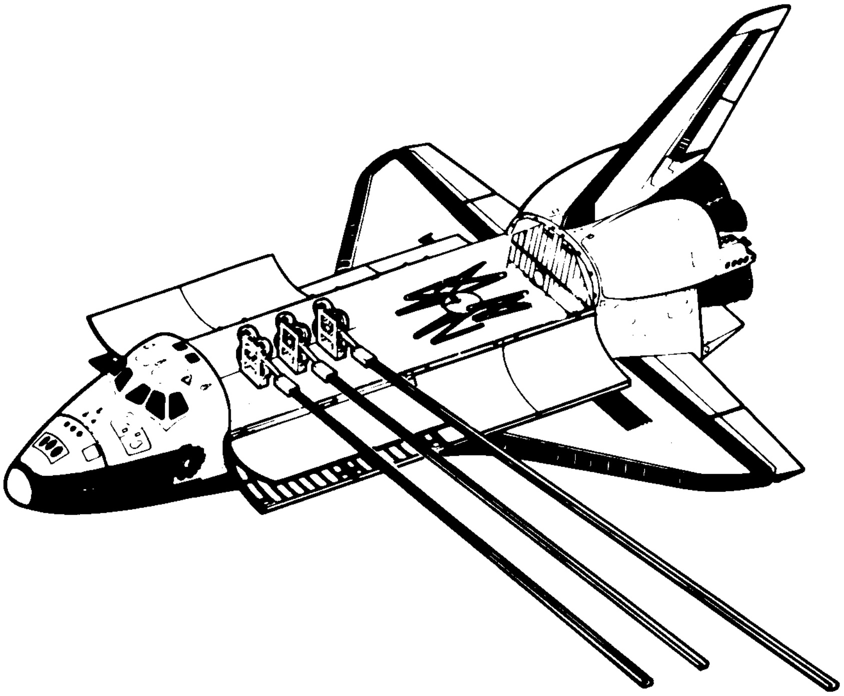

Figure 8. On-orbit rolltrusion.

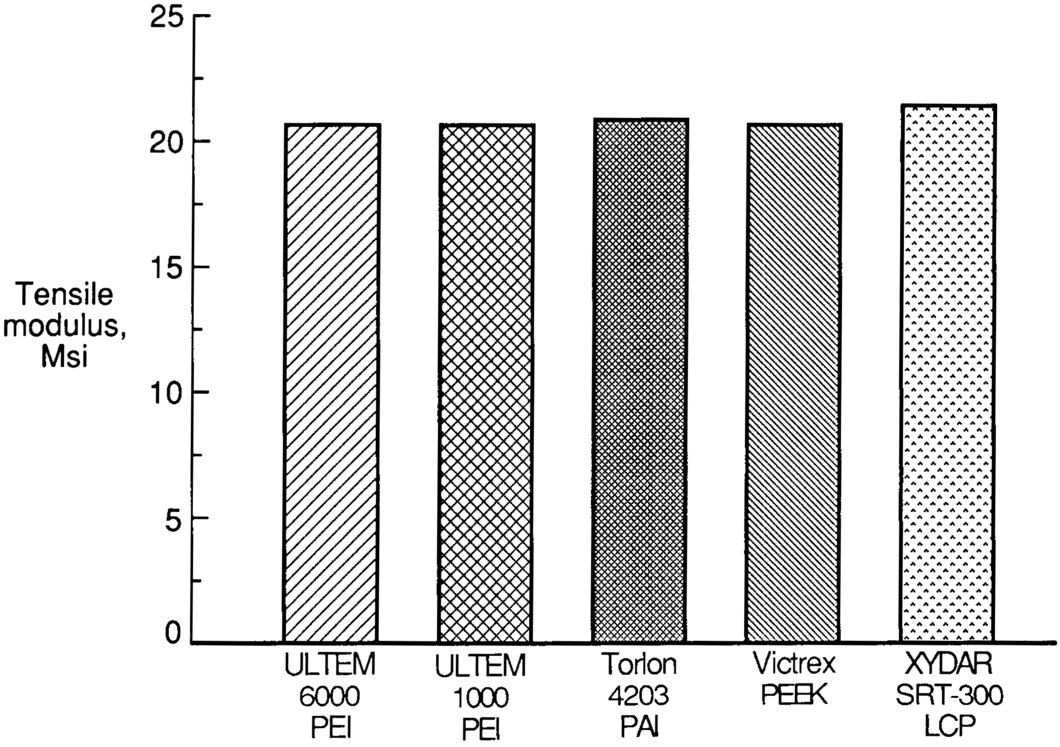

Figure 9. Thermoplastic/graphite moduli. 1 Msi = 1 × 10^6 psi.

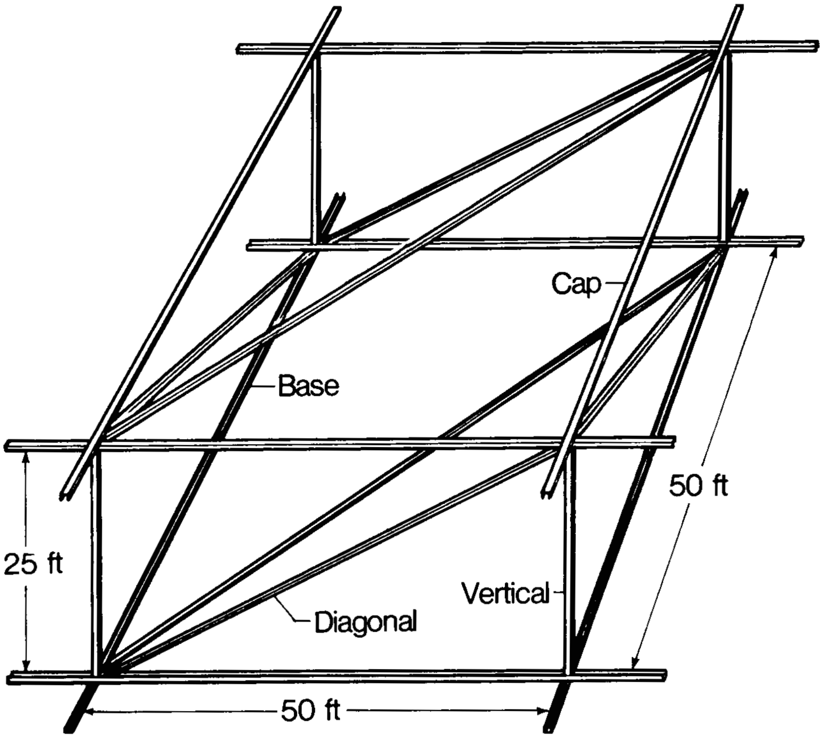

Figure 10. Channel structure.

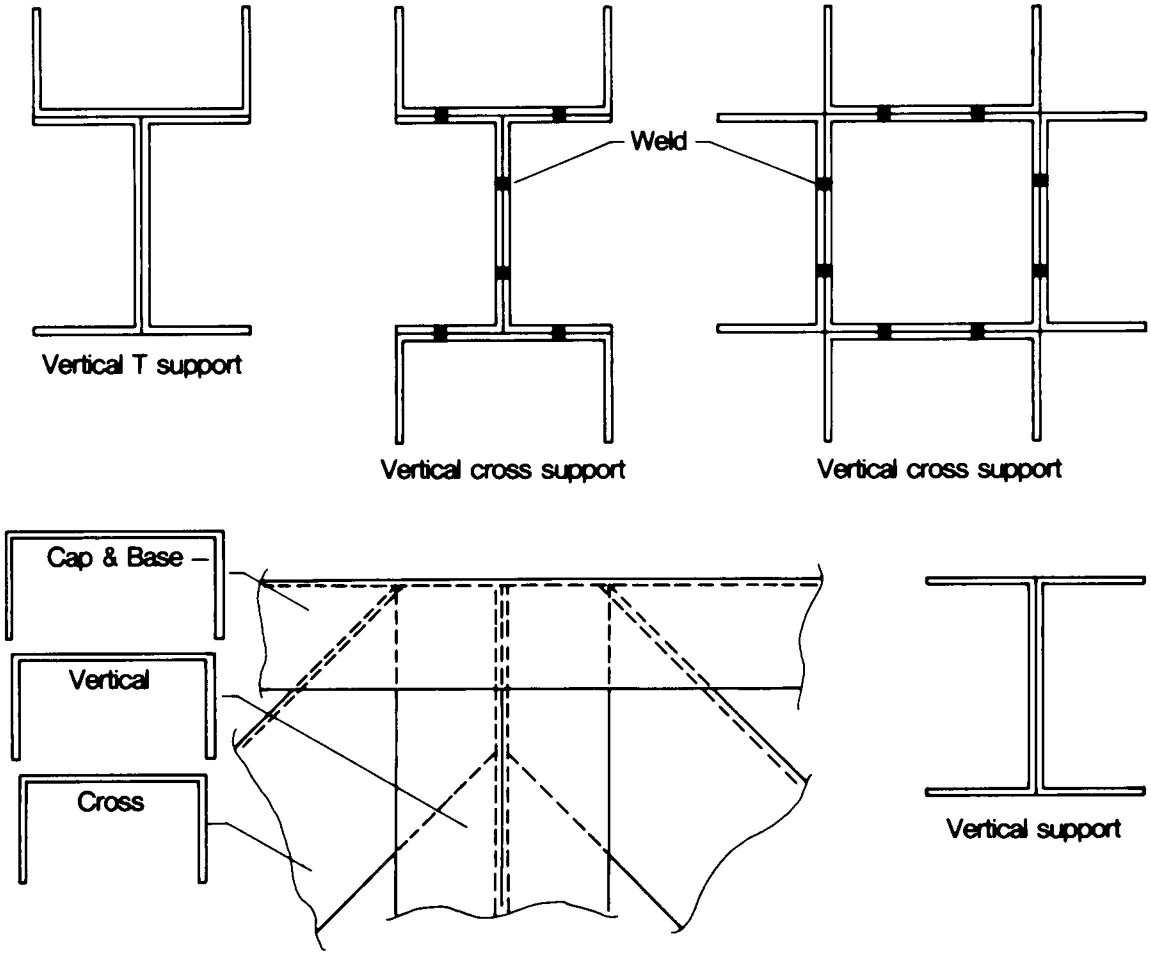

Figure 11. Channel concepts.

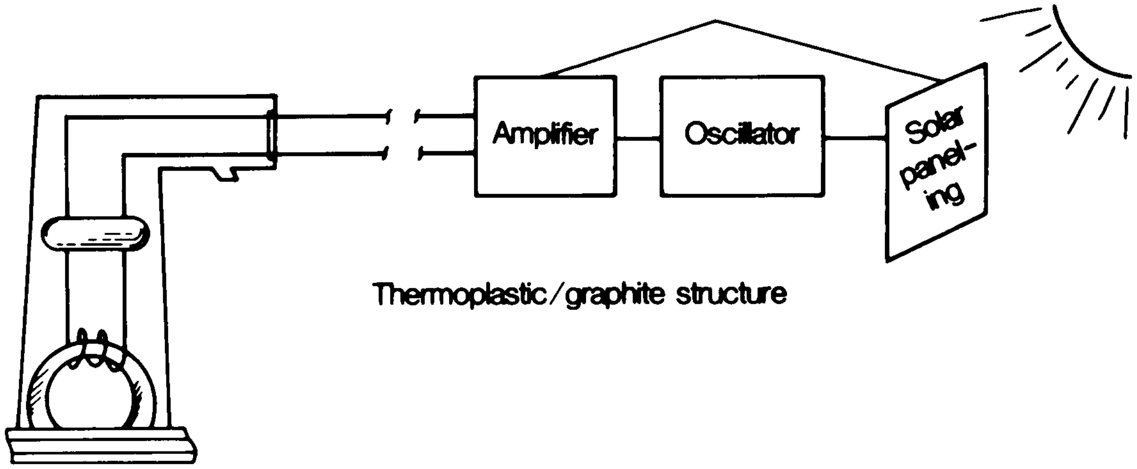

Figure 12. Schematic of toroid gun.

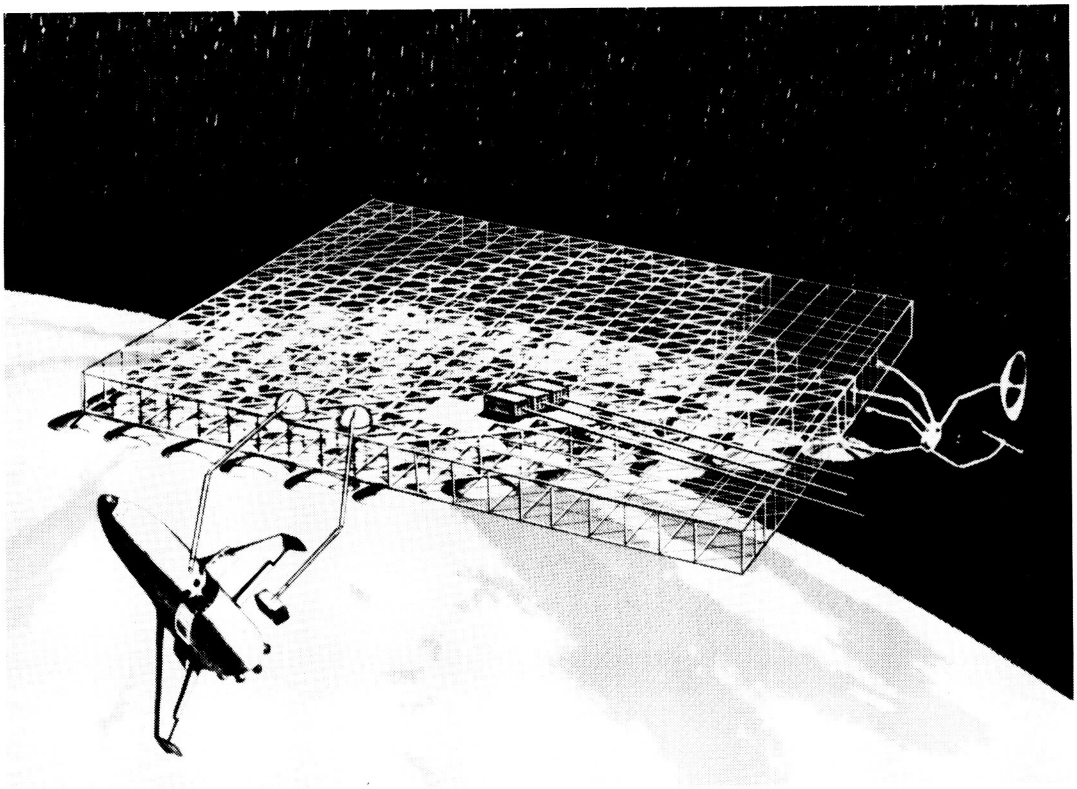

Figure 13. On-orbit manufacturing.

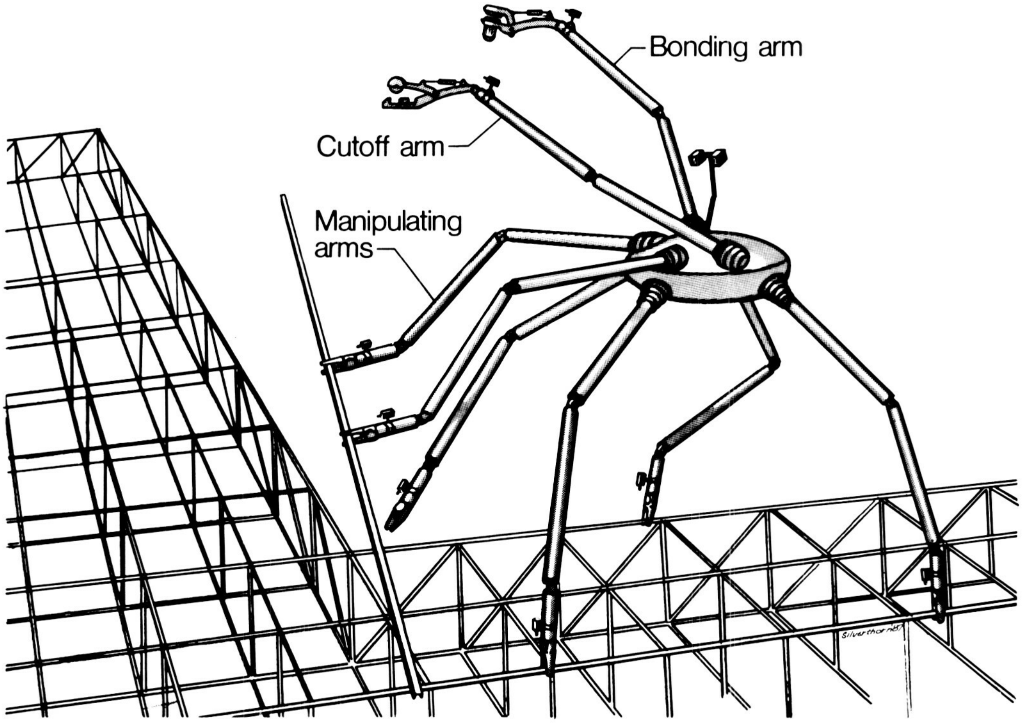

Figure 14. Space spider robot.

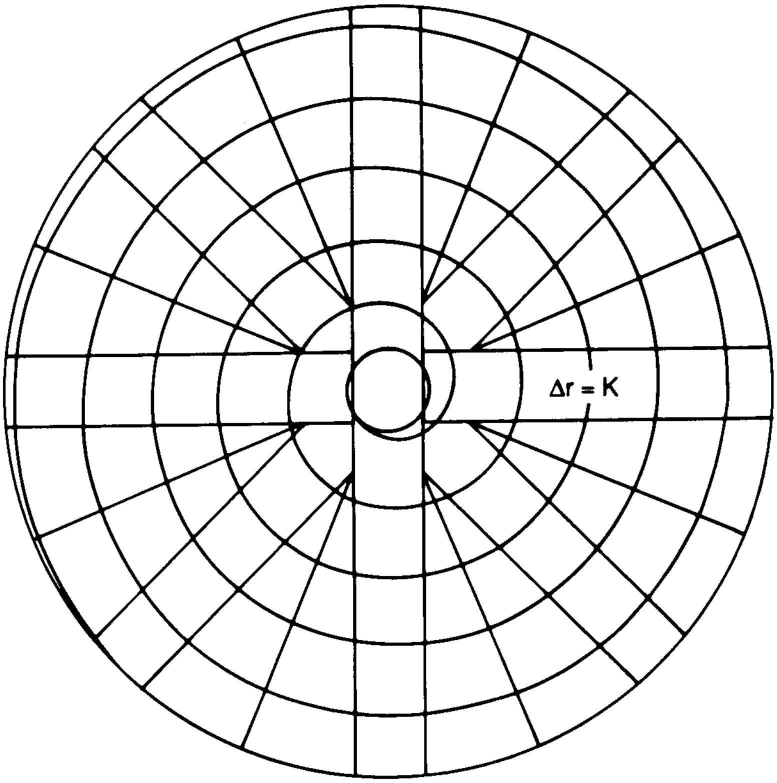

Figure 15. Archimedean spiral concept.

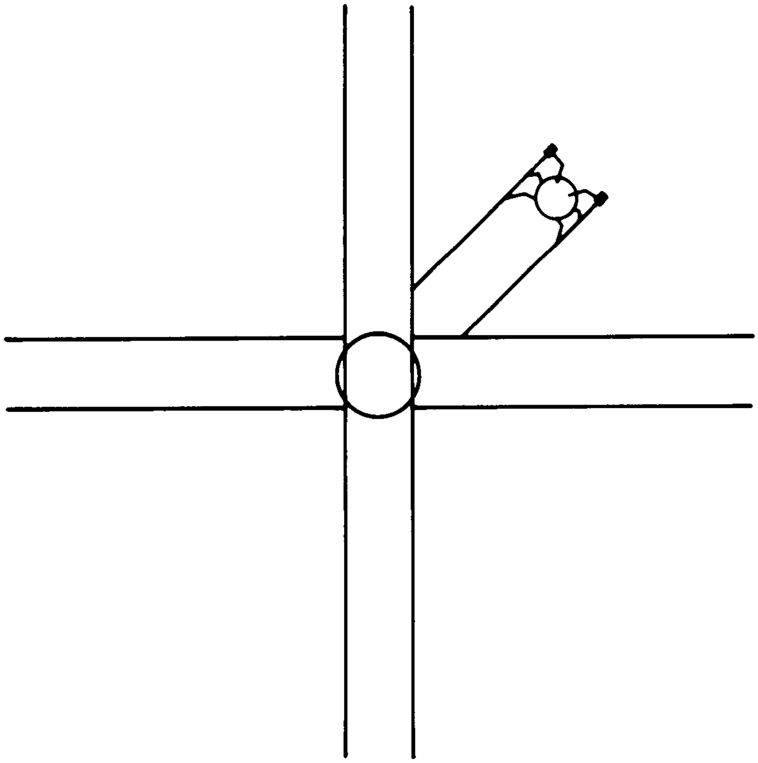

Figure 16. Robotic fabrication.

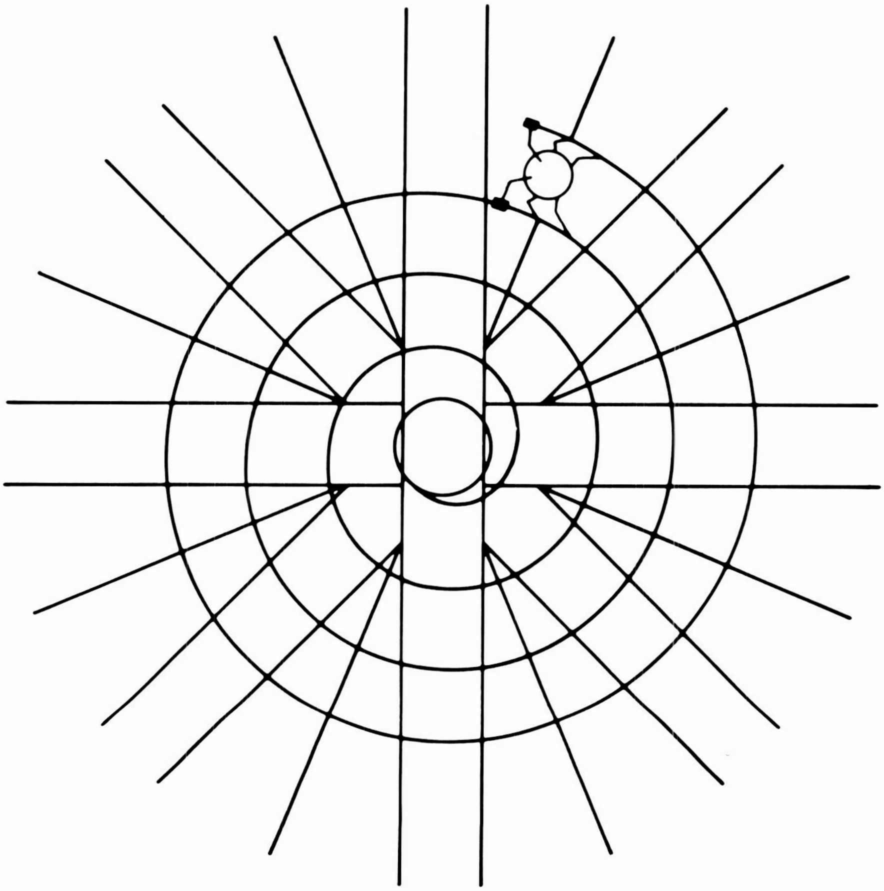

Figure 17. Continuous spiral.

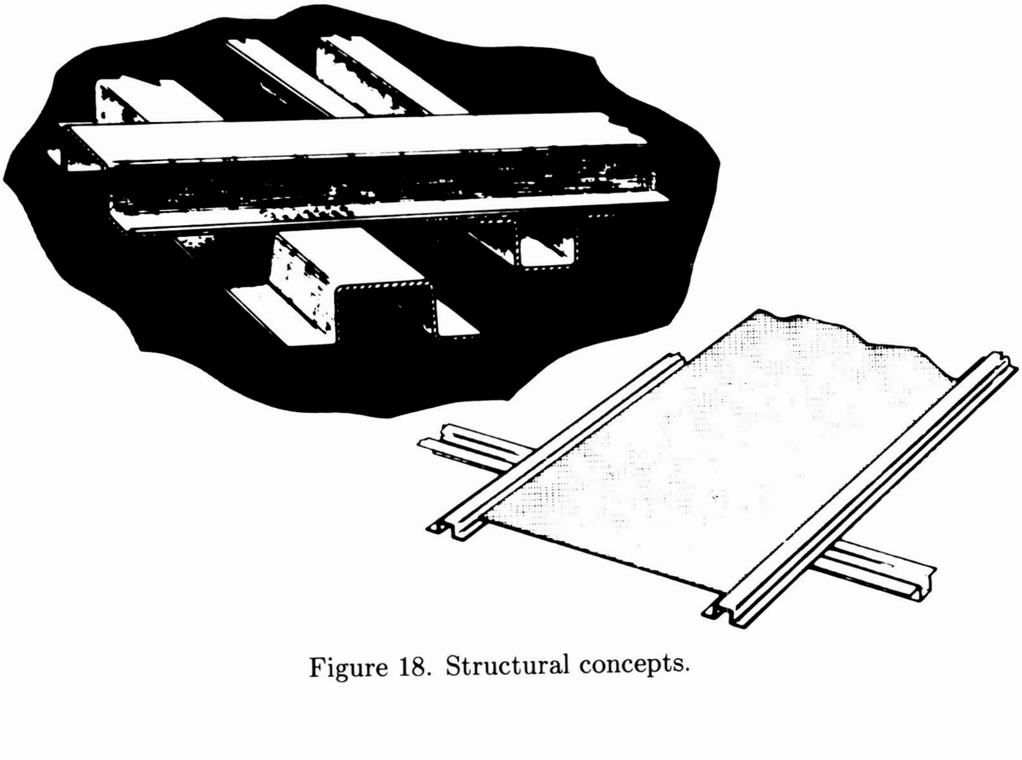

Figure 18. Structural concepts.

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